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THE HAWAIIAN PLANTERS' RECORD

Relative positions at harvest of cane, lodged and erect (control), used in a study of the effect of lodging on juice quality.

SECOND QUARTER 1942

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Vol. XLVI SECOND QUARTER 1942 No. 2

A quarterly paper devoted to the sugar interests of Hawaii and issued by the Experiment Station for circulation among the plantations of the Hawaiian Sugar Planters' Association.

In this issue:

Juice Quality Affected by Lodging:

Lodging of sugar cane, generally caused by heavy winds or rains, results in a poorer quality and an actual loss of sugar especially in that part of the stalk which remains recumbent. These effects are apparently not modified by supplying extra nitrogen fertilizer to cane which has already received nitrogen at a high level.

New Caledonian Cockroach Parasite:

Illustrating the habits of a brilliant blue-green wasp that destroys our large household cockroaches. This wasp was imported from New Caledonia and reared in the laboratory.

Notes on the Temporary Establishment of Insect and Plant Species on Canton Island:

The recent establishment on Canton Island of certain insects is described. Reasons are given for believing that these insects, as well as plants sprouting from ocean-borne seeds as a result of recent ample rainfall, will eventually die out due to the almost certain recurrence of semi-arid conditions.

Filter-Cake Compost:

The decomposition of fresh filter cake under laboratory and field conditions and the nutritive value of the final product—filter-cake compost—are discussed. The results of the investigations showed that decomposition was completed within from 5 to 7 months, and that the fresh filter cake was adequately supplied with the necessary nutrients for the development of the organisms which were responsible for its decomposition.

Are There Possibilities in Subsoil Fertilization?

Soils removed from the surface foot and from the subsoil of cultivated cane fields, although differing widely in their available nutrient content, have been made to produce comparable yields when adequately fertilized. This fact suggests that subsoil fertilization, to more nearly equalize the availability of nutrients in surface soils and subsoils, ought to result in a more extensive and efficient root system for sugar cane.

Boron in Some Hawaiian Soils and Crops:

The boron content of Hawaiian soils, soil-forming materials, irrigation waters, and economic crops has been determined. Consideration is also given to boron fixation and the availability of water-soluble soil boron. The total soil boron is highest in surface soils and ranges from 4 to 56 p.p.m. Old uneroded soils from high rainfall regions contain the most total boron. Water-soluble boron is also highest in surface soils and ranges from 0.4 to 3.2 p.p.m. A significant relationship is found between soil pH and water-soluble boron. Hawaiian soils fix boron from dilute solutions of boric acid. The distribution of boron in various organs of sugar cane, pineapple plants and other crops grown in both high and low boron mediums is discussed. A normal crop of sugar cane removes less than 0.5 pound of boron per acre.

Rainfall Evaluation as an Aid to Irrigation Interval Control:

A method of rainfall evaluation, based on hundreds of concurrent soil-moisture observations and temperature records, has been devised and is fully described. This evaluation of rainfall in terms of day-degrees has been of great assistance in controlling irrigation intervals at Waipio Substation inasmuch as the control is relatively simple to operate, and since seasonal variations are automatically taken into account by the use of day-degrees to measure intervals.

The table of rainfall evaluation for adjusting irrigation intervals at Waipio is described, and the procedure for its use explained and demonstrated. Tables for rainfall evaluation on eight other standard types of soils are available. When selected judiciously for specific local soil types, these tables should operate with as satisfactory results as have been obtained at Waipio.

Juice Quality Affected by Lodging

By R. J. Borden

Statements to the effect that the quality of the juice of canes which have lodged is poorer than that of erect canes are not uncommon, but it is somewhat difficult to find actual data to support such assertions. However, the tendency of some otherwise good cane varieties to lodge causes discrimination against such canes in several sugar-producing countries and, therefore, the issue becomes one in which we in Hawaii should be interested, since we have a tendency to accept this growth habit without serious question, justifying our complacence with the realization that lodging generally signifies a heavy cane tonnage, and that there is little we can do about it anyway. But, this attitude should not prevent our search for the facts, and we conducted a well-controlled skirmish test* to find out what actually happens to cane which "goes down."

Plan: The plan which we used to study this objective was as follows: 36 Mitscherlich pots containing Manoa soil were each planted with two single-eye cuttings of 31–1389 cane on January 29, 1941 and grown under uniform conditions until September 1. To find out whether an extra application of nitrogen, made sufficiently in advance of the time the cane "goes down" to be quite completely taken up, would alter the effects of lodging, half of the pots (Series A) were given an extra application of ammonium nitrate. One month later, 9 pots from this Series A and a corresponding 9 pots from a control Series B (which did not get the extra nitrogen) were laid on their sides so that the stalks were left in a horizontal or lodged position (Position No. 2); the remaining 9 pots were left in their original erect positions (Position No. 1). From this time until the canes were harvested on Feb. 3, 1942, similar treatment was given to all pots.

At the time of assigning the individual pots to their respective positions, each primary stalk was permanently marked at its uppermost dry-leaf internode; this mark provided a means for dividing these stalks at harvest into (1) a lower section, which was already mature stalk before the positional differential was imposed, and (2) an upper section which matured thereafter.

Observations: Within 3 days after imposing the horizontal position, the stalks had turned up their tops at approximately a 45° angle to their basal portions, and at 6 days this angle was at 90° and the top portions of the stalks were again erect and remained so until harvested. It should be recorded that these 6 days came during a period of bright sunny weather.

The accompanying photograph (Fig. 1) shows the position of the lodged canes as they were at harvest; also the position of the "controls" which were erect throughout the whole growing period.

Results: At harvest the primary stalks from each replicate were separated into their lower and upper portions, and these sections were then measured, weighed, and crushed for juice analyses. In addition the millable cane portions of all suckers

* Project A–105 No. 166.

were composited, according to treatments, since there was an inadequate amount of millable cane from the sucker growth to provide for individual analyses of juices.

The harvest results are summarized in Table I and the data have been studied

Fig. 1. Positions of lodged canes and their "controls." The pair on the right received extra nitrogen.

for their significance by an analysis of variance of the 2 x 2 factorial plan which was used. Since there was no evidence of any interaction between the two nitrogen levels and the two positions, the averages (except for the sucker growth) as listed in Table I are from the 18 replicates of each of the main factors.

TABLE I

(a) EFFECTS ON *LOWER* PORTIONS OF STALKS

Measurement	Stalk position		Nitrogen applied	
	No. 1—erect	No. 2—lodged	A=extra N	B=control
Purity	94.3 *	91.5	92.4	93.3
Pounds cane	1.93*	1.61	1.82	1.73
Y%C	15.6 *	13.7	14.5	14.8
Pounds sugar	.30*	.22	.27	.26
Length (ft.)	2.46*	2.06	2.29	2.23

(b) EFFECTS ON *UPPER* PORTIONS OF STALKS

Measurement	Stalk position: No. 1—erect	No. 2—lodged	Nitrogen applied: A=extra N	B=control
Purity	93.8 *	90.7	91.4	93.2*
Pounds cane	2.00	2.20	2.09	2.12
Y%C	15.1 *	13.5	14.0	14.6
Pounds sugar	.30	.30	.29	.31
Length (ft.)	2.51	2.68	2.57	2.62

(c) EFFECTS ON SUCKERS

Measurement	Stalk position: No. 1—erect	No. 2—lodged	Nitrogen applied: A=extra N	B=control
Purity	90.1	87.9	.88.5	89.6
Total lbs. cane	3.31	2.47	3.20	2.58
Y%C	13.7	12.3	12.8	13.1
Total lbs. sugar	.45	.30	.41	.34

* Only these figures are proved significantly greater than the corresponding figure for the respective differential. No statistical analyses were made on the data from suckers as these replicates were not kept separate.

Discussion: The only significant effect that was measured on these canes, from the difference in the nitrogen applied, was that a slightly poorer purity was found in the crusher from the upper portions of those stalks which had received the extra nitrogen; this is an effect which has been measured many times previously in other investigations. Furthermore there was no indication of any modification of the measured effects of lodging by the different amounts of nitrogen that were applied. Hence no further discussion of the nitrogen factor in this present study need be indulged in.

The effects on sugar cane stalks which lodge or "go down" are quite clearly seen to be chiefly effects on the cane quality, and we note that the crusher juice purity and the yield-per-cent-cane (Y%C) of both the lower portions of the stalks which were mature before lodging took place, and of the upper portions which matured thereafter, were quite similarly affected. It might also appear that the juices of millable cane from the suckers which grew after the cane had lodged had also been adversely influenced, although it is a bit difficult to conceive why this should be so.

Although it had been assumed that a comparable distribution of the 36 pots had originally been made between the two positional differentials, and that each stalk had been fairly marked at its uppermost dry-leaf internode, the measurements and cane weights taken at harvest, which show significantly more cane on the lower portions of the stalks which had remained erect, may indicate that our original distribution of replicates was faulty, for we have no well-established grounds for believing that the length of this mature stalk portion would actually shrink, although we might concede a loss in weight if it is assumed that some sugars were used up in bringing the tops from their horizontal to an erect position again. However, we make these measurements, as secured, a matter of record.

The loss in sugar which has occurred in the lodged cane is significant only for the lower section of the stalk which was already mature when lodging occurred; this sugar loss appears to be in the neighborhood of 25 per cent. No similar effect was found on the recoverable sugar from the upper parts of the stalks which

matured after lodging occurred. Perhaps a fairer estimate of the total loss of sugar from the lodged canes is contained in a comparison of the total amounts of the cane and sugar recovered from the 18 pots which carried the lodged canes and the other 18 with their erect stalks; the difference is still a considerable amount and is seen to be primarily due to the poorer juice quality from the cane that "went down," e.g.

Position	Total lbs. cane	Total lbs. sugar	Avg. Y%C
1—Erect	74.23	11.43	15.4
2—Lodged	71.23	9.66	13.6
Difference	3.00	1.77	1.8
% lost	5.0	15.5	11.7

Conclusion: A definitely poorer juice quality has been measured as an effect of lodging, and this in turn has resulted in an actual loss in recoverable sugar. Apparently these effects from lodging were not altered by increased nitrogen fertilization.

The New Caledonian Cockroach Wasp *(Ampulex Compressa)* in Hawaii

By Francis X. Williams

Illustrated by W. Twigg-Smith

In May 1940 the Experiment Station of the Hawaiian Sugar Planters' Association sent the writer to New Caledonia to study the insects of economic importance of that large island. Inasmuch as Noumea, capital of New Caledonia, is a stopping point for the Pan American Airways' Clipper ships plying between the California coast and New Zealand and, touching of course at Honolulu, it is important to know what pests, particularly those attacking sugar cane, are found in New Caledonia so as to better guard against their accidental importation here.

A large collection of economic insects was made during the four-month stay in New Caledonia. This collection is being studied and will be reported on at a later date. Living specimens of a large wasp that preys on cockroaches were introducted into Honolulu, and are apparently established here. This insect, technically known as *Ampulex compressa,* forms the subject of the present paper.

The habits of this wasp, a brilliant, chiefly blue-green jewel of an insect nearly an inch long, have been known to science in some detail for 200 years. It inhabits parts of Asia, Africa, island of St. Helena, islands of the Indian Ocean as well

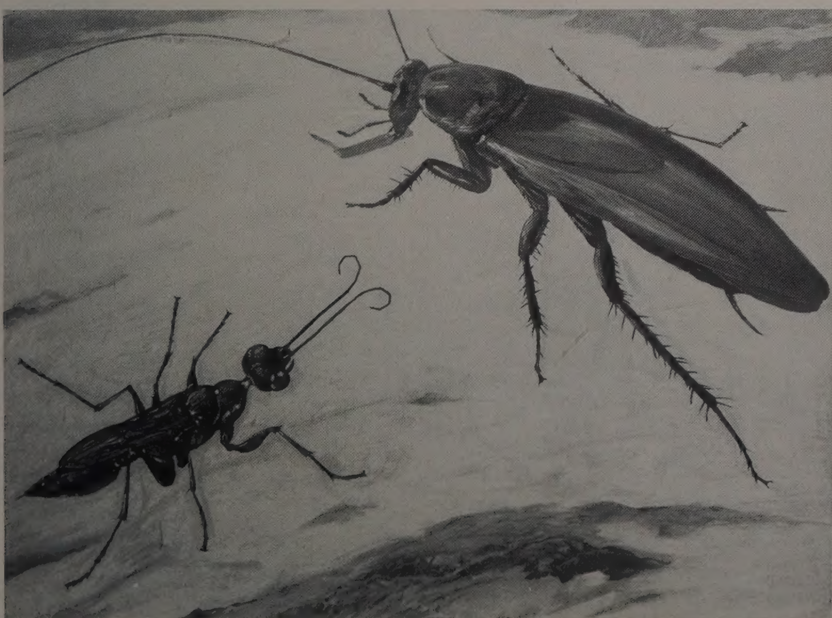

Fig. 1. The wasp finds the cockroach.

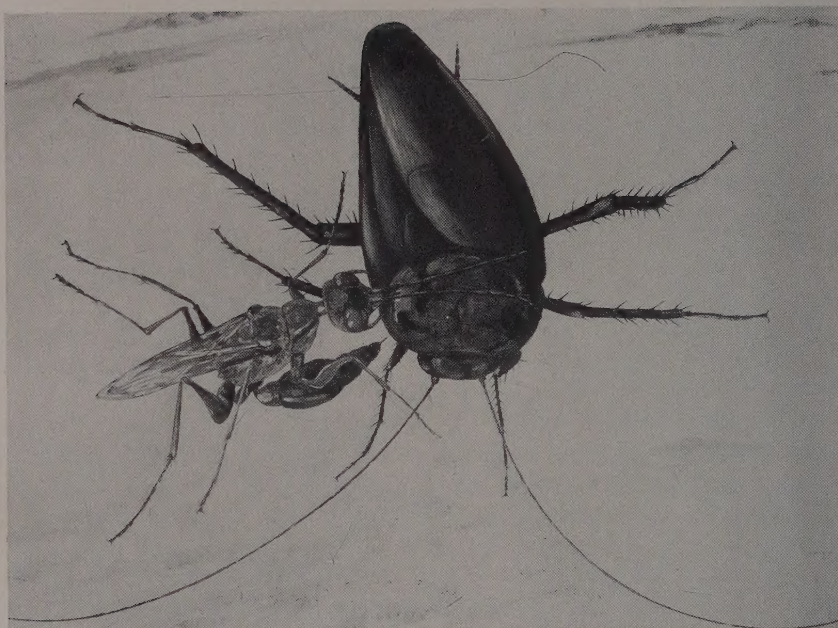

Fig. 2. She attacks—stinging the cockroach in breast and throat.

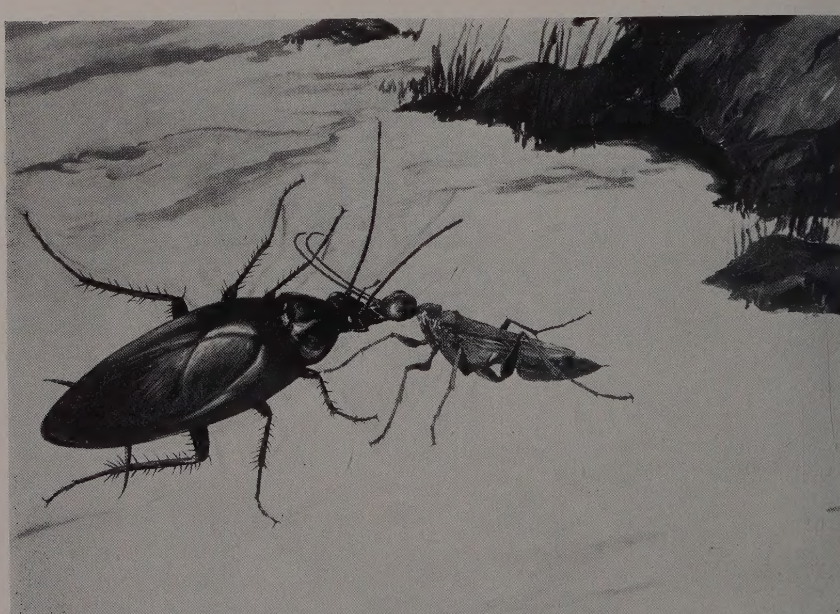

Fig. 3. The disabled cockroach is dragged into a hole.

as the island of New Caledonia. It is an inveterate enemy of our common large cockroaches. In Noumea it is called the "cantharide," and in the summer time—our winter season—is abundant there; but it was still quite rare in early November when Mrs. Williams and I were preparing to return to Honolulu. Of the six female *Ampulex* seen in Noumea, four were captured. Of these, one was injured in its capture and a second died within three weeks. The other two were taken with us to Honolulu via Pan American Airways and lived 74 and 102 days respectively. Also brought back from Noumea were a number of large cockroaches parasitized by the three wasps, of which the two long-lived ones parasitized several dozen additional cockroaches during their captivity in Honolulu. This living *Ampulex* material has been sufficient for its establishment on the island of Oahu. Wasps at large have now been seen in Honolulu for well over a year after their liberation.

The several illustrations accompanying this paper clearly indicate the chief activities of *Ampulex compressa*.

Fig. 1 shows an *Ampulex* that has just discovered a large cockroach. The wasp measures four-fifths of an inch and the cockroach is twice as long and several times her bulk. The very alert wasp, her antennae held close together forward, is manouvering to one side of the still unsuspecting cockroach in preparation for a lightning attack upon it.

In Fig. 2 the wasp has leaped forward to grip the thoracic plate of her prey, edge on, between her clypeus and labrum above and her curved mandibles beneath. Almost at the same instant she directs her extensile abdomen forward beneath her chest to sting the cockroach in its soft underpart between the legs and in the throat, with a semi-paralyzing effect.

In Fig. 3, following the regular procedure, *Ampulex* has cut off a considerable length of the cockroach's antennae and is dragging it by the base of one antenna to a hole she has discovered. She drags her more or less resisting prey into this retreat and glues an egg to the base of one leg of its middle pair. Now she imprisons her prey by plugging up the hole with debris.

In Fig. 4 we have taken out this parasitized cockroach and placed it on its back to show the wasp's egg in place (left) and, a few days later, the same cockroach showing the wasp grub that has developed from the egg (right). Note that the parasite is in such a position on the cockroach that it can not usually be rubbed off or injured by any movement. The wasp grub thus feeds externally on its host for three or four days. Somehow it has secured nourishment with the help of its delicately spine-tipped jaws. It sheds its skin for the fourth time to acquire a strong stout-toothed pair of jaws with which it immediately bites its way into the cockroach's body and devours the interior. The cockroach soon perishes.

Fig. 5 (left) illustrates a cockroach cut open to expose the feeding *Ampulex* wasp grub within its abdomen. The dead and internally devoured cockroach soon stiffens into a mere shell. Herein the full-grown wasp grub spins a silky brown cocoon (Fig. 5, right) enveloping a hard dark cask within which, sooner or later, depending on the season, it changes into a pupa.

In due time the pupa within the cocoon produces the brilliant blue-green wasp that bites its way out to freedom (Fig. 6).

The wasp's life, as egg, larva and pupa, on and within the cockroach, varies

Fig. 4. The wasp lays an egg on the cockroach, the egg hatches into a grub, and the grub eats its way into the cockroach.

Fig. 5. The cockroach lives only a few days longer while the grub feeds upon it. When the grub is full-grown, it spins a cocoon inside the cockroach.

from a little more than one month to four months or more.

Three kinds of cockroaches are successfully used by *Ampulex*. These are: *Periplaneta americana,* the large brown roach; *Periplaneta australasiae,* a smaller but still quite large roach; and *Neostylopyga rhombifolia,* a somewhat rare wingless species of large size and conspicuous color pattern.

This beautiful blue-green wasp readily attacks her prey within the confines of a large jar, and she as readily accepts the carton tube, plugged at one end, as a nest hole in which to store her cockroach prey. Her several activities—the fierce attack, the dragging-in of the subdued roach, and the stuffing of the stored tube with the debris at hand—have been witnessed here by many people and with great interest.

Ampulex compressa lives a long time. The longest record for the male is 85 days. Several others survived for over two months.

The following table shows the longevity of sixteen females and the number of cockroaches stored by some of these wasps:

Captured in New Caledonia	Died	Days longevity	No. cockroaches stored
October 15, 1940.........	Nov. 4, 1940.....	20	Not recorded
" 17, 1940.........	Dec. 30, 1940.....	74	About 65
" 31, 1940.........	Feb. 10, 1941.....	102	About 78
Hatched in Honolulu			
January 6, 1941........	May 11, 1941.....	125	85
" 23, 1941........	" 12, 1941.....	109	88
May 12, 1941........	June 12, 1941.....	31	20
" 15, 1941........	" 20, 1941.....	36	25
" 15, 1941........	Sept. 11, 1941.....	119	65
" 25, 1941........	" 9, 1941.....	107	55*
June 9, 1941........	Oct. 10, 1941.....	123	49*
" 20, 1941........	" 9, 1941.....	111	41*
Sept. 15, 1941........	Dec. 16, 1941.....	92	33*
October 16, 1941........	Feb. 12, 1942.....	129	46*
" 6, 1941........	" 17, 1942.....	134	43*
" 13, 1941........	March 12, 1942.....	150	39*
" 24, 1941........	April 1, 1942.....	159	57*

* Indicates that these individuals were supplied with cockroaches at longer intervals, of from two to several days. Aged wasps were usually too stiff, short-winded and of insufficient vigor to successfully cope with a large cockroach. Thus such wasps, and rather undersized ones too, were often supplied with small (younger) cockroaches so as not to overtax their strength.

The wasp has been liberated chiefly in Honolulu where it has been seen at large over a period of many months. It is being shipped to the other islands of the Hawaiian group. To date over 200 females have been set free.

How this wasp will affect the population of large cockroaches remains to be seen. Many cockroaches will be destroyed by it, but it is doubtful if these hardy and adaptable pests will thereby be greatly reduced. However, every cockroach enemy helps.

Fig. 6. A few weeks later a new-born wasp comes out.

Notes on the Temporary Establishment of Insect and Plant Species on Canton Island

By R. H. Van Zwaluwenburg

Canton Island, a typical coral atoll in mid-Pacific at 2° 49′ south latitude and 171° 40′ west longitude and the first station southward on the Pan American Airways route from Hawaii to New Zealand, presents interesting problems involving the temporary establishment of certain insect and plant species. The insect and plant problems involve the variance in annual rainfall; those concerning the establishment of plant species involve, besides, the ocean currents which transport floating seeds to the island. These notes are based on observations made on Canton during some 16 weeks spent there in the late summers of 1940 and 1941.

Numerous small low islands in the central Pacific are relatively near, but Canton is well removed from high island archipelagoes and major land masses. Approximate distances in nautical miles, stated in round numbers, are as follows:

From Canton to	Samoa	700 miles
	Fiji	1000 "
	Tahiti	1550 "
	Hawaii	1600 "
	Solomons	1700 "
	New Britain	2150 "
	New Guinea	2300 "
	Galapagos	4900 "
	Ecuador	5500 "

Although properly considered to be a dry island,* Canton has a rainfall which varies greatly from year to year and which at times is relatively heavy, providing, at least temporarily, conditions favorable for the establishment of certain plants and insects. Weather data for Canton are available only since the latter part of 1937. The rainfall totalled 8.7 inches in 1938; it has since increased year by year until in 1941, 83.7 inches had fallen by the end of August. Similarly wide variations are recorded from nearby islands (Bryan, l.c., p. 16): Malden (a dry island) from 3.9 to 93.5 inches; and Fanning (a wet island) from 47.4 to 208.8 inches. It seems inevitable that eventually Canton will again experience periods of very low rainfall.

Two years of good rains have resulted in a thriving growth of native vegetation on Canton at the present time. On areas described as "desert" in the spring of 1939, there is a heavy cover of *Sida fallax* Walpers (shoulder high in many places) associated with *Boerhaavia diffusa* L., *Triumfetta procumbens* Forster, *Portulaca lutea* Solander and three species of bunchgrass (Digitaria, Eragrostis and Lepturus). (See Fig. 1.)

* Bryan, Edwin H., Jr., 1941. American Polynesia—Coral Islands of the Central Pacific. Tongg Publishing Company, Honolulu, 208 pp., numerous maps and figs.

During the spring and fall of 1940 an occasional travel-tattered straggler of the widespread butterfly *Hypolimnas bolina* L. was seen, but never more than a single one at a time, and separated by long intervals of time. By August 1941 this butterfly was abundant over the mile or so of island immediately south of the main channel leading from the lagoon into the sea. Strangely enough it occurs nowhere

Fig. 1

Views taken on Canton Island two years apart showing contrast in vegetation (resulting mainly from growth of Sida) between a dry year and a wet one. The photograph on left taken by A. C. Browne in October 1939 (total rainfall for 1939, 18 inches); the other in September 1941 (1941 rainfall, through August, 84 inches). Both are looking northward.

else on the island, despite the presence everywhere of Sida presumed to be the foodplant of its caterpillar. None of the other foodplants of Hypolimnas larvae recorded elsewhere occurs on Canton. The butterfly, the sexes of which are dimorphic, has several varieties, two of which have been seen on Canton. The establishment of Hypolimnas on Canton appears to be the direct result of the present abundant food supply in the form of Sida. A return to semi-arid conditions, with an attendant reduction of Sida foliage, would probably result in the sharp reduction of this insect's numbers, if not in its complete extinction.

The Monarch butterfly, *Danaida archippus* (Fabr.), has arrived singly at least once at Canton within the past year and a half,* but so far has not established itself there in spite of the presence, as a cultivated plant, of crown-flower, *Calotropis gigantea* R. Brown (family Asclepiadaceae), a favorite foodplant of its larva.

A conspicuous feature during the fall of 1941 was the large numbers in all parts of the island of the common "globe skimmer" dragonfly, *Pantala flavescens* (Fabr.), which was not seen at all on Canton the year before. Also present this year but not last, less numerous than Pantala, is the smaller, reddish dragonfly *Diplocodes bipunctata* (Brauer);† this species has been recorded from Australia and various Pacific islands including the Ellice group, Samoa, Tonga, Tahiti and New Caledonia. The presence of dragonflies on Canton this year can be traced to the forma-

* Reported in October 1940 by R. R. Danner.

† Both dragonflies were identified by Dr. F. X. Williams.

tion and persistence of rain-fed pools, where immigrant individuals lay their eggs and in which their young can maintain themselves.

It seems probable that some or all of the above-mentioned insects, as well as others similarly capable of traveling long distances, have been established on Canton at one time or another in the past. The fact that the present establishment of the three discussed is recent suggests that conditions of food and water favorable for their maintenance are only temporary; that establishment and local extinction succeed each other as favorable and unfavorable conditions alternate; and that the present colonies of these particular species will in turn die out when severe drought recurs.

The prevailing winds at Canton are from the east or slightly south of east, seldom exceeding 25 miles per hour. Similarly, the principal ocean current is one moving westward along the equator. That the eastbound equatorial countercurrent also affects Canton appears doubtful. Currents apparently reach the island at times from the southeast, for a paddle found on the southwest coast is said by K. P. Emory, ethnologist of the Bishop Museum, to be of the southeastern Polynesian type (Society, Cook or Austral Islands). Pumice stones, obviously waterborne and not of local origin, are especially numerous on that part of Canton lying east of the lagoon. In 1941 for the first time, as far as is known, a few glass balls such as are used as fishnet floats by the Japanese were found on the beach at practically all cardinal points of the island. A piece of copal gum, showing evidence of having been afloat for a long time, was also found during the past summer. This is a secretion of certain leguminous trees, some of which occur in South America, others in Africa. To get information concerning the currents reaching the island, wood samples were taken from some of the numerous stranded trees to be found on both east and west coasts; these have not yet been identified.

Between December 1940 and February 1941 there were some weeks of strong westerly winds which attained a velocity of 55 knots. The effect of these prolonged gales on the normal ocean currents, though temporary, must have been considerable. Drift-borne seeds were absent or at least inconspicuous on the Canton beaches the year before, but by August 1941 they were a striking feature of the shore line everywhere. It is assumed that their presence is a result of the gales of the previous winter. Drift seeds collected were identified by E. L. Caum as follows:

Myristica sp. (Myristicaceae)
Entada scandens (L.) Bentham (Leguminosae-Mimosoideae)
Inocarpus edulis Forster (Leguminosae-Papilionateae)
Mucuna spp. (4) (Leguminosae-Papilionateae)
Caesalpinia crista L. (Leguminosae-Caesalpinioideae)
Canarium sp. (Burseraceae)
**Barringtonia speciosa* Forster (Lecythidaceae)
Terminalia catappa L. (Combretaceae)
Cerbera odollam Gaertner (Apocynaceae)
Unidentified spp. (3)

* The nearest islands to Canton on which Barringtonia is known to occur are Samoa, the Wallis and Futuna group, and Fiji.

In addition the writer identified seeds of the coconut* (*Cocos nucifera* L.), the kukui (*Aleurites moluccana* (L.) (Willdenow), and a hala (*Pandanus* sp.). The species named are all native or naturalized in Polynesia, as are also some species of Myristica, Mucuna, Canarium and Pandanus.

Seeds of many of the species listed had sprouted after stranding. Between 35 and 50 coconut sprouts were estimated to be still present in September along the entire 27-mile perimeter of the island, but these were only a small fraction of the total number of coconuts cast up. Some of the hazards attending the survival of seedling plants from drift seeds are obvious: hermit crabs (*Coenobita olivieri* Owen) shred the husks of coconuts and eat out the contents of the sprouted nuts; flood tides drench many seedlings with sea water; in at least one case high water buried a sprouted palm deep in sand. So the complete failure of any of the above-named plant species to become established on Canton in the past (all of the coconuts growing on the island are known to have been planted by man) is not surprising when, to the hazards already mentioned, are added the inevitable recurrent shortages of rain.

* The nearest islands on which coconuts are growing, with their approximate distances in sea miles from Canton are: Enderbury 37, Sydney 100, Hull 120 and Gardner 190. Dr. C. H. Edmondson (Occ. Papers, Bernice P. Bishop Museum, 16: 293–304) recently tested the viability of coconuts after floating them in sea water for various lengths of time. In his experiments 110 days was the longest period in salt water after which coconuts still sprouted. "A conservative estimate of the distance that might be traversed in that time, if carried by a favorable current, is about 3000 miles."

Filter-Cake Compost

By J. P. Martin

The purpose of this article is to summarize the results of the investigations conducted on the rate of decomposition of filter cake under laboratory and field conditions and on the nutritive value of filter-cake compost. These studies were started January 1940 at the request of Dr. H. L. Lyon, and progress reports have appeared from time to time in the Director's Monthly Reports.

The value of humus or organic matter in the soil for securing normal plant growth has long been recognized. Humus is derived from plant and animal residues which are decomposed by microorganisms and is that residual portion of organic matter which undergoes little or no further decomposition. Humus in soils varies from about 0.5 to 12 per cent and is usually concentrated in the upper soil layer, and its presence in the soil is essential for maintaining the proper fertility level. It acts as a storehouse for nutrients upon which the plants and soil organisms draw during their development; it improves the tilth, moisture-holding capacity, and the chemical and physical properties of a soil. Sandy or clay soils are greatly improved by the addition of organic materials. Humus prevents rapid changes in the soil reaction to acidity and alkalinity, and it serves to neutralize toxic conditions in the soil. Humus improves the soil as a medium for those organisms which in turn convert raw materials into valuable plant nutrients.

Filter cake is a by-product of sugar production and is the filtered residue obtained from clarifying raw-cane juices. It contains from about 8 to 10 per cent of finely divided fiber, 0.2 to 1 per cent sugar, 70 to 80 per cent moisture, and some nitrogen, phosphoric acid, potash, lime, and other mineral elements. It amounts to from 4 to 6 per cent of the weight of cane, that is, around 5 pounds of filter cake are obtained from 100 pounds of cane, thus showing that there is a very large amount of raw material to draw upon.

Filter cake is made up chiefly of plant residues, and during the process of decomposition the soil organisms assimilate large quantities of inorganic nitrogen and mineral elements, thus making these materials temporarily unavailable for growing crops. When decomposition reaches completion, large numbers of these organisms die and disintegrate and portions of the mineral elements become available for green plants. When undecomposed plant material such as fresh filter cake is applied to growing crops it becomes necessary to apply additional nutrients, otherwise the organisms will compete with the plants for nitrogen and other elements and the result is generally at the expense of the plants. Therefore it is advisable to compost plant residues from filter cake or cane trash outside the field and apply the compost later. The chemical nature of the final product depends largely on the original plant residues and on the rate and extent of their decomposition.

The most essential elements for rapid decomposition of filter cake by microorganisms are nitrogen, phosphorus, calcium, and potassium. Filter-cake compost, as the result of microbial decomposition, is reduced in volume and weight, and

darkened in color. The organisms principally responsible for the rotting of filter cake are bacteria and fungi, which are low forms of plants devoid of chlorophyll, and which depend on other plants or plant materials for their livelihood. Many organisms are harmful while others are indispensable for the manufacture of animal and industrial products and for the final disposal by decomposition of all plant and animal materials.

Under favorable environmental conditions fresh filter cake is attacked immediately by organisms. The more important compounds attacked are as follows: carbohydrates such as sugars, starches, and cellulose, the latter being the fibrous material in the plant; proteins and their derivatives or the nitrogen-bearing constituents of the plant; fats and waxes; lignins, which are responsible for the stiffness or woodiness of plants; and mineral elements and various complex chemical compounds. Carbohydrates and some proteins decompose rapidly; cellulose, fats, and some nitrogenous substances decompose more slowly; while lignins, waxes, and resins are highly resistant to decomposition.

Laboratory Studies: For these studies 70 bags of fresh filter cake were secured from Oahu Sugar Company and the material spread on a large concrete platform, thoroughly mixed, and partially air-dried for three weeks. A composite sample of the partially air-dried material was collected and analyzed for certain constituents, the results of which are given in Table I under the heading of "Before Composting."

TABLE I

AN ANALYSIS* OF FILTER CAKE PRIOR TO AND AFTER COMPOSTING FOR SIX MONTHS AT MAKIKI

	Per cent (original basis)	
	Before composting	After composting
Moisture	68.39	68.36
Calcium, CaO	1.343	†
Potash, K_2O	0.145	†
Phosphate, P_2O_5	0.860	†
Total Nitrogen, N	0.367	0.49
Total Carbon, C	8.69	5.64
Carbon-nitrogen ratio, C/N	23.7 : 1	11.5 : 1

* Analysis by Chemistry Department.
† These nutrients would still be present after composting.

In studying the rate of decomposition of the fresh material, varying amounts of different fertilizers were added to and mixed with 100-pound portions of the partially air-dried filter cake. The filter cake used in the control series (with no fertilizers added) had a moisture content of 68.39 per cent, or 31.61 pounds of dry matter in each 100-pound portion. During the composting period, starting January 11, 1940 and ending August 2, 1940, each 100-pound portion in the treated and control series was held in a separate container. Frequent inspections of the filter cake in all series were made and sufficient moisture was added to maintain moist conditions at all times. After the filter cake had been composting for several months the material in each container was removed, examined, mixed, and replaced in its respective container.

On August 2, 1940, or within a little less than 7 months, the material in the control series was found to be thoroughly decomposed and at this time weights

and moisture determinations of each container were recorded. The results are presented in Table II.

TABLE II

LOSS IN DRY WEIGHT OF FILTER CAKE AFTER COMPOSTING

Container	% moisture	Pounds of material: Wet basis	Pounds of material: Dry basis	Difference in dry weights before (31.61 lbs.) and after composting
1	67.36	76.0	24.81	6.80
2	66.84	75.75	25.12	6.49
3	57.98	63.00	26.47	5.14
		Average....	25.47	6.14

It is thus shown that during the composting period there was a loss of 6.14 pounds or 19.42 per cent of dry matter. This difference may be accounted for by the release of gases (mainly carbon dioxide) which were formed by the microorganisms during the process of decomposition. In this series it was noted that the original volume was reduced to one half, the material was well decomposed, and that very little fiber from bagasse remained.

In other series it was noted that the rate of decomposition of the fresh material was not materially increased when additional fertilizers (chiefly nitrogen from ammonium sulphate) were added to the original material before composting.

In Table I the data show that the fresh filter cake before composting had a carbon-nitrogen ratio (C/N) of 23.7 : 1, while after decomposition the ratio was reduced to 11.5 : 1. Such a wide ratio as in the case of the former (23.7 :1) would cause a nitrogen deficiency in plants. The organisms utilize many of the carbon compounds in filter cake as a source of energy as well as for structural purposes with the result that the carbon-nitrogen ratio is reduced. If this ratio becomes extremely narrow, for example 5 or 6 : 1, it indicates that large amounts of nitrogen have been accumulated.

Under laboratory and field (as shown later) conditions it was evident that fresh filter cake was thoroughly decomposed by microorganisms within 6 or 7 months and that it was adequately supplied with the necessary elements for the development of the organisms which were responsible for its decomposition. The fact that no additional fertilizers were essential for complete decomposition is of considerable economic importance when preparing the final product from filter cake which in itself is low in plant nutrients.

In pot experiments it was demonstrated that the fully decomposed filter-cake compost as prepared in the control series was an excellent medium for the growth of the following crops: tomato, corn, bean, beet, radish, and sugar cane (31–1389). In other pot studies it was shown that fresh or partly decomposed filter cake was definitely not suitable for the growth of the crops just mentioned.

Field Studies: During October 1940 a location was selected at Oahu Sugar Co., Ltd., by Mr. Hans L'Orange, where fresh filter cake from the mill could be hauled in order to study its decomposition under field conditions. Immediately following this date the plantation started and continued to haul filter cake for a period of several months, and at the end of the hauling period many hundreds of

Fig. 1. General view of filter cake being composted at Oahu Sugar Company.

Fig. 2. Lower edge of filter cake compost pile shown in Fig. 1.

tons of filter cake had been deposited in the compost pile. The site selected was along a railroad track where on one side the land sloped rapidly while on the other side there was less slope. With this arrangement the labor required for unloading the cars of fresh filter cake was reduced to a minimum. On November 13, 1940 the filter cake pile was examined and thereafter periodic examinations were made. On November 23, 1940 it was noted that where the filter cake was 5 or more feet in depth it had started to heat. On December 17, 1940 the heating of the filter cake was still in evidence and it was noted that decomposition had started in the upper surface foot; it was also observed that a heavy growth of mushrooms (chiefly *Coprinus atramentarius* and some *Agaricus campestris,* both of which are edible) had developed. Photographs of the filter-cake pile taken on this date by W. Twigg-Smith are shown in Figs. 1, 2, and 3.

A composite sample of fresh filter cake from the compost heap was collected December 17, 1940, and the results of the chemical analysis by the Chemistry Department follow:

	Per cent	
	Dry basis	Original basis
Moisture, H_2O	....	75.5
Calcium, CaO	0.78	.191
Potash, K_2O	0.252	.062
Phosphate, P_2O_5	4.31	1.056
Total nitrogen, N	1.22	.299
Total Carbon, C	33.77	8.27
Carbon-nitrogen, C/N	27.7:1	

These data show that the material (before composting) with its wide carbon-nitrogen ratio of 27.7 would be unsuitable for plant growth. It is recognized that the per cent of the various constituents, as reported above, will vary from time to time, but it was found that the fresh filter cake was adequately supplied with the necessary elements for the development of the organisms which were responsible for its decomposition. This was also the case when fresh filter cake was composted under laboratory conditions.

Under field conditions the filter cake was decomposed within from 5 to 7 months. In parts of the compost pile where the filter cake had been piled too deeply for the most rapid decomposition, the material on the bottom was not thoroughly rotted. It should be pointed out that abnormally dry weather conditions prevailed during the composting period and that no additional moisture was added. It is felt that the rate of decomposition would have been increased if normal rainfall had occurred.

The filter-cake compost prepared under field conditions at Oahu Sugar Co., when tested for its nutritive value on corn, (U.S.D.A. 34), eggplants (Black Beauty), beets (Asgrow Wonder), radishes (Early Scarlet Globe), and beans (Stringless Green Pod), was found to greatly stimulate the growth of all plants. In using filter-cake compost for vegetable culture it is suggested that the material be applied as a surface dressing and then worked into the soil before the seeds or plants are planted.

Filter-cake compost which is well decomposed is slowly transformed into humus. The organisms which cause fresh filter cake to rot require aerobic con-

ditions, that is they require oxygen—humus is an aerobic product. Fresh filter cake should therefore be spread in layers not more than 3 to 5 feet in depth while it is undergoing decomposition. If fresh filter cake is piled too deeply anaerobic conditions are created, and organisms other than those under aerobic conditions

Fig. 3. Mushrooms growing on the surface of the filter cake being composted at Oahu Sugar Company.

develop and products, chiefly gases such as hydrogen, nitrogen, methane, carbon dioxide, carbon monoxide are formed. If possible it is advisable to turn the material over occasionally in order to insure a more rapid rate of decomposition. The material should be kept moist at all times; usually normal rainfall is sufficient to meet the moisture requirements. Under field conditions the material should be ready to use at the end of from 5 to 7 months.

The decomposition of plant residues in the form of roots and stubble in gardens and cane fields adds large quantities of humus to the soil. Composting plant materials such as grass cuttings, leaves, entire plants, etc., is a common practice and a compost heap may be found in many gardens.

Acknowledgment: The writer greatly appreciates the cooperation received from Mr. L'Orange, manager, Oahu Sugar Company, Ltd., for furnishing the filter cake used in the laboratory studies and for conducting the field studies at Waipahu.

Are There Possibilities in Subsoil Fertilization?

By R. J. Borden

In his discussion "Why Root Studies?", W. P. Alexander (1) says "Plantation practice should emphasize the need of securing cane plants with the deepest root systems possible . . . . If root growth can be promoted in the lower depths our ratoons will be more stable . . . . Large cane yields are absolutely dependent on the right foundation of roots that are healthy and are expanded to the greatest extent."

Cane root studies by some investigators have shown evidence of well-developed root systems which extend especially into and also below the second foot of well-drained soils. Shaw (4), et al, in 1931 made field excavations at Waipio which revealed well-developed root systems of several cane varieties in the second foot of soil even at the early age of 3 months; and at 8 months, an excellent distribution was found even in the third foot of soil. Evans (2) studied a POJ 2878-Uba seedling which at 18 months had "roots in the second foot of soil that were nearly as numerous as those in the first foot," and many other varieties showed variable extents of root development below the first foot of soil. Jensen (3) found that although the roots in subsoils are fewer, they have longer and larger rootlets than surface roots.

Weller (5) presented evidence that a root showed greater branching when it came into the region of buried fertilizers. Evans (2) found evidence that the deeper roots from a harvested crop continue to function longer for the subsequent ratoon than the superficial or surface roots; furthermore that there is a tendency for this surface root system to become still more shallow as further ratoons are grown, and also that under conditions of drought the surface roots ceased to absorb nutrients, yet absorption of mineral substances by the deeper roots was continuous.

The opinion is rather well established that cane tonnages would be indirectly increased, as root systems are directly increased to provide larger root-feeding surfaces, from improved soil aeration. Wolters (6) found a marked correlation between root growth and top growth, and implied that the soil's textural and structural characteristics which govern aeration were responsible for root penetration. Evans (2) found a correlation coefficient of +.85 between root and top growth in monthly harvests of White Tanna, and believes that breaking up the subsoil promotes a deeper root growth, and attributes this to better aeration. The beneficial effect of tilling ratoons is assumed to be due to the opening-up of the soil and its better aeration. Jensen (3) presents evidence of shallow, retarded root growth where the soil is shallow and the subsoil impervious to air and water.

Although it is probably true that the formation or instigation of secondary roots is dominated by aeration, their further growth and development will be of

little extent unless adequate moisture and nutrients are available within the increased root-feeding zone. Thus tillage methods *alone* may not bring about the desired deep root penetration. Whereas the tillage operations presume to loosen the soil and let in more air and water, they also release some mineral nutrients which are important contributors to the increased root growth noted thereafter. Wolters (6, p. 78) tells us of a practice of hook-subsoiling which was at one time used by Oahu Sugar Company on the older ratoon fields, and he indicates that the better physical condition was responsible for its effectiveness. He says "Some of the old roots are ripped out, the soil is aerated and softened so that the fertilizer soon works into the root zone where it is readily and effectively utilized by the plant. The roots are stimulated by the presence of fertilizer, soon causing a rapid development into the loosened soil and later stimulating heavy stooling and shoot growth." We would be inclined to argue that the effectiveness noted was primarily due to the fact that the fertilizer got well down into the lower soil zones through the subsoil grooves.

It is doubtful if many soils of our cultivated fields actually lack oxygen in their second-foot layers, for we see very little evidence of slow drainage which would indicate inadequate pore space; the surplus water drains through rapidly, and air will follow this water. Thus it is unlikely that air itself has been a limiting factor in the root development of our sugar cane crops.

On the other hand it is a well-known fact that phosphates and nitrogen have had marked effects on root development. This is especially true of phosphate which promotes both root elongation and branching. The effect of nitrogen apparently is to inhibit root penetration and to promote profuse branching. Hence by our common field practice of applying nitrogen and phosphate on the surface soil, we tend to develop strong surface roots and to discourage the deep penetration of roots which is considered a more desirable type of root system. This common plantation practice of fertilization may be why some of our root studies have shown that only 30 per cent of the cane roots were found below the upper 8 inches of soil. What possibilities for increased yields, then, might we expect from deeper, more extensive cane root systems which would undoubtedly develop if the available nutrient levels in our subsoils were more nearly equal to those found in the surface soil?

The foregoing discussion is offered by way of an introduction to a consideration of data which have been gathered incidental to our testing, by the Mitscherlich method, of samples of soil from many of our cooperative field test areas during the past 10 years. These soil samples have come from widely scattered areas and were taken by many different individuals. To avoid the confusion which sometimes attends the identity of the actual point of differentiation between surface soils and subsoils in many of our cane lands, the samples were taken from each of two depths; those from 0–12″ were designated as surface soils, and those from 12″ to 24″ were called subsoils. A four-inch soil auger was used, and each soil sample was a composite from not less than 20 borings. Each sample was shipped to Makiki where it was air-dried just sufficient for screening and mixing. Subsequently it was potted, fertilized, and planted as follows:

No.	Identity	No. of pots	Root medium	Fertilizer Gms. N	Gms. P_2O_5	Gms. K_2O	Indicator crop
1	No P_2O_5	2	Soil only	1.1	0	1.5	Panicum grass
2	N 6P K	2	" "	1.1	9.0	1.5	" "
3	No N	2	" "	0	9.0	1.5	" "
4	No K_2O	3	¼ soil; ¾ sand	1.1	3.0	0	Sudan grass
5	N 2P K	3	" "	1.1	3.0	1.5	" "

When the Sudan grass seed matured, all 12 pots were harvested and their dry weights secured. Due to seasonal variations, this maturity was usually reached between 70 and 90 days. Thus we have yields from surface soil and subsoil, each with and without P_2O_5, N, and K_2O, which can be set up for a comparison of the relative responses from each of these three nutrients.

Individual data are presented as a supplement in Table II, for such interest as they may have for the plantations concerned; they will not be discussed separately. But in Table I, we have summarized the results by Island groupings, and further discussion will relate to these data.

TABLE I

SUMMARY (True averages)

Identity of measurement and conditions	Soil depth	Hawaii	Kauai	Maui	Oahu	All Islands
1—Grams dry weight* without P_2O_5(1)	0–12″	117	109	167	180	126
" " " " "	12–24″	54	31	118	139	59
2—Grams dry weight* with P_2O_5(1)	0–12″	255	240	243	233	243
" " " " "	12–24″	252	233	237	225	237
3—% gain for P_2O_5	**0–12″**	**81**	**126**	**71**	**30**	**111**
" " " "	**12–24″**	**329**	**761**	**188**	**75**	**532**
4—Grams dry weight* without N(2)	0–12″	48	41	45	37	42
" " " " "	12–24″	28	23	28	28	25
5—Grams dry weight* with N(2)	0–12″	255	240	243	233	243
" " " " "	12–24″	252	233	237	225	237
6—% gain for N	**0–12″**	**521**	**497**	**528**	**544**	**513**
" " " "	**12–24″**	**943**	**918**	**757**	**722**	**885**
7—Grams dry weight† without K_2O(3)	0–12″	74	87	142	120	97
" " " " "	12–24″	74	63	125	103	80
8—Grams dry weight† with K_2O(3)	0–12″	108	129	156	136	129
" " " " "	12–24″	112	118	149	133	124
9—% gain for K_2O	**0–12″**	**47**	**51**	**11**	**14**	**40**
" " " "	**12–24″**	**52**	**94**	**20**	**30**	**66**

* Panicum grass.
† Sudan grass.
(1) With same N and K_2O.
(2) " " P_2O_5 and K_2O.
(3) " " N and P_2O_5.

Phosphate: When no phosphate fertilizer was applied, the average dry weight of panicum grass adequately fertilized with N and K_2O only, and grown on 166 subsoils, was approximately 53 per cent less than from the corresponding surface soils. Separately, the Kauai subsoils produced 72 per cent less than their surface soils, the Hawaii subsoils 54 per cent less, the Maui subsoils 30 per cent less, and

Oahu subsoils only 23 per cent less than their surface soils when no phosphate was applied. On the other hand, when both surface soils and subsoils were similarly and abundantly supplied with phosphate, there was less than 3 per cent difference in their respective yields. Thus it would appear that the phosphate fertilization of these subsoils was quite as effective as applications within the surface soils. If such an assumption can be made from these data, then we may infer that the effectiveness of phosphate fertilizer will not be diminished if it is placed in the subsoil root-feeding zones; and from our previous discussion we have reason to believe that it would be advantageous for deep root development to have the phosphate well below the surface layers of soil.

The figures showing the percentage gain from phosphate fertilization over no phosphate, on both the surface soils and subsoils, are interesting. Thus from the same amounts of P_2O_5 applied, the gains from subsoil fertilization were considerably greater than from surface soil applications. This was especially true of the Kauai and Hawaii soils and indicates the great differences which exist in the available phosphate supply of the two soil depths. Doesn't this suggest possibilities of better crops and more ratoons if we could build up the available phosphate supply of these subsoils and bring it somewhat nearer the levels in the surface soils?

Nitrogen: As was to be expected panicum grass yields, produced without nitrogen on soils taken from continually cropped cane fields, were generally quite low. The fact that the subsoils without N produced only about 60 per cent of the yields from the surface soils is in accordance with the usual finding that the available nitrogen supply in soils generally decreases with their depth. However, when supplied with identical amounts of nitrogen fertilizer (plus adequate P_2O_5 and K_2O), these subsoils were not significantly poorer than the surface soils in their ability to produce satisfactory crops.

The percentage gains in dry weights harvested, from the use of identical amounts of nitrogen fertilizer, were higher from the subsoils than from the surface soils, and as was the case with phosphate, this was especially true for the Kauai and Hawaii soils. Does this suggest the use of a material such as ammonium phosphate to be applied early in conjunction with a subsoiling operation that would allow this fertilizer to be put down in the groove made by the subsoiler?

Potash: The dry weights of Sudan grass produced without potash were considerably less on both surface soils and subsoils from Kauai and Hawaii than from Maui and Oahu; this is in line with other data which have shown lower amounts of available potash in regions with heavier rainfall.

On the Hawaii soils when no potash was supplied, Sudan grass yields from subsoils were equal to the yields from surface soils, whereas with potash the yields from the subsoils were 10 per cent better than from surface soils. Without potash, the Kauai subsoils produced 30 per cent less than surface soils but only 9 per cent less when potash was supplied. The Maui and Oahu subsoils produced respectively 12 per cent and 14 per cent less than their corresponding surface soils without potash fertilizer, but less than a 5 per cent yield difference was obtained between these surface and subsoils where potash had been applied.

The percentage gain from a standard amount of potash applied to subsoils from Kauai, Maui, and Oahu was about twice that obtained from the surface soils, but there was little difference in this figure for the Hawaii soils. Apparently then there is less difference in the available potash levels between the surface soils and subsoils from the island of Hawaii than was found to be the case with phosphate or nitrogen; hence, subsoil fertilization with potash may not offer the same possibilities here which are indicated for these other two plant foods. But for the soils on the other three islands, there may be something gained by building up the available potash levels of the subsoils to a point somewhat nearer the surface-soil levels of this nutrient.

Conclusion: Granted that the data which have been recorded herein need a liberal interpretation, because the responses measured on both surface soils and subsoils were not actually obtained *in situ,* and with no attempt to minimize the effects from aeration which necessarily accompany all soil sampling, preparation and potting, yet we have shown that this aeration was in itself insufficient to make the subsoils produce satisfactory yields. Without N, or P_2O_5, or K_2O, there is only one instance (i.e., without K_2O in Hawaii soils) where the subsoils yielded as well as the surface soils; and certainly in the pot technique we have used, all soils were well aerated. On the other hand, well-fertilized subsoils have been made to produce yields which were not significantly different from similarly fertilized surface soils.

So the idea still persists that since few of our cane land soils really lack for air in their second-foot root zone, the failure of masses of roots to extend therein is chiefly due to a low available nutrient supply. If this condition can be corrected and this subsoil nutrient supply can be more nearly equalized with that of the surface soil, the desirable objective, cited by Alexander in our opening paragraph, should be easier to reach.

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SUPPLEMENT

TABLE II

AVERAGE GRAMS DRY WEIGHT HARVESTED

Plantation	No. of soils	Indicator crop = Panicum grass: Without P_2O_5 Surface	Without P_2O_5 Subsoil	With N, P_2O_5 and K_2O Surface	With N, P_2O_5 and K_2O Subsoil	Without N Surface	Without N Subsoil	No. of soils	Indicator crop = Sudan grass: Without K_2O Surface	Without K_2O Subsoil	With N, P_2O_5 and K_2O Surface	With N, P_2O_5 and K_2O Subsoil
HAWAII												
Waiakea	4	106	37	286	291	133	70	4	71	78	101	107
Hilo	1	164	70	309	282	25	13	3	74	80	157	148
Pepeekeo	4	93	22	244	231	28	18	4	77	81	107	115
Honomu	1	50	22	222	196	33	27	1	47	51	64	71
Hakalau	3	86	43	258	250	47	22	5	53	57	99	105
Kaiwiki	14	115	82	270	265	37	22	16	67	70	95	105
Hamakua	5	81	39	202	199	37	29	7	73	69	101	102
Paauhau	2	147	50	307	303	43	21	2	103	85	134	121
Haw'n Agr.	6	147	39	233	231	45	22	6	79	77	112	120
Hutchinson	5	156	55	254	259	44	27	6	94	81	124	120
Kohala	1	141	65	255	279	88	47	1	140	127	150	144
All Hawaii*	46	117	54	255	252	48	28	55	74	74	108	112
KAUAI												
Kilauea	13	64	24	225	223	43	21	25	62	42	116	107
Lihue	37	115	27	250	245	42	23	47	98	74	139	130
Grove Farm	15	120	23	239	225	37	23	22	94	58	141	121
Kipu	2	119	22	240	235	42	27	2	55	42	103	90
Koloa	4	145	44	272	265	59	33	5	110	88	145	131
McBryde	4	112	19	247	238	31	20	4	114	86	140	119
Kekaha	9	110	71	201	193	33	22	12	73	61	93	90
All Kauai*	84	109	31	240	233	41	23	117	87	63	129	118
MAUI												
Maui Agr.	2	157	77	213	208	33	26	8	141	126	155	148
H. C. & S.	3	167	110	203	215	24	21	12	142	127	150	144
Wailuku	4	211	189	235	234	40	29	13	148	133	158	152
Pioneer Mill	1	177	105	281	263	39	30	5	149	117	167	154
Kaeleku	2	81	37	328	293	102	39	2	89	82	143	159
All Maui*	12	167	118	243	237	45	28	40	142	125	156	149
OAHU												
Waimanalo	1	134	141	148	150	41	35	1	111	105	113	119
Kahuku	1	278	231	323	283	50	46	1	159	155	177	177
Waialua	4	156	76	232	229	45	32	4	118	92	138	139
Ewa	17	181	146	231	222	33	25	17	115	99	132	128
Waianae	1	211	166	270	287	55	40	1	173	155	186	163
All Oahu*	24	180	139	233	225	37	28	24	120	103	136	133

* True averages.

Boron in Some Hawaiian Soils and Crops*

By T. Tanada and L. A. Dean
Hawaii Agricultural Experiment Station

Only in comparatively recent years has it been generally recognized that boron is required by higher plants for normal growth. Today physiological disorders of some twenty-odd cultivated plants have been shown to be due to the lack of sufficient boron. The boron content of the soil solution and of irrigation water is usually relatively low; yet, if this concentration is increased by only a few parts per million, a condition which is toxic to many plants may arise. The range in concentration of boron at which normal growth takes place varies with the species of plant and is quite narrow for many. Hence, determining the amount of boron in soils and irrigation waters is of twofold importance from the standpoint of practical agriculture.

It was the purpose of this investigation to determine the distribution and amount of boron in soils, soil-forming materials, irrigation waters, and plants significant to Hawaiian agriculture.

Methods of Analysis

All the boron analyses were made by the procedures proposed by Berger and Truog (1).

Water-soluble boron: The water-soluble or presumably available boron is extracted by boiling 20 gm. of soil with 40 cc. of water for 5 minutes and clarifying.

Total boron: The total boron is extracted from soils by a sodium carbonate fusion.

Boron in plant materials: The boron in the plant materials is determined after dry ashing and dissolving in dilute sulfuric acid.

Distribution of Boron in Hawaiian Soils

Horizontal distribution of boron:

This study of the distribution of boron in Hawaiian soils entailed a consideration of the amounts of total and water-soluble boron in different soils and also the vertical distribution in various soil horizons. Table I is presented to illustrate our findings concerning the distribution of boron in the various soil horizons. The profiles from Kona and Halemanu offer an interesting contrast between young and old soils, the former being younger than the latter. Both soils were formed under comparable conditions of rainfall and elevation. In general, the total boron content of the old surface soil is considerably higher than that of the younger soil. On the other hand, there appears to be a lower water-soluble boron concentration in the older soil. In all instances the total and water-soluble boron decrease with

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TABLE I

HORIZONTAL DISTRIBUTION OF TOTAL AND WATER-SOLUBLE BORON IN SOME HAWAIIAN SOILS

Soil No.	Origin of sample	Depth	Total boron p.p.m.	Water-soluble boron p.p.m.	Remarks
40–213a	Kona, Hawaii	0– 8″	14	0.9	Soil
40–214b	" "	8–16″	17	0.5	"
40–215c	" "	16–24″	13	0.4	"
40–215c$_1$	" "	16–24″	5	0.2	Partly decomposed aa lava
37–357a	Halemanu, Oahu	0–12″	46	0.7	Soil
b	" "	13–23″	14	0.3	"
c	" "	23–39″	6	0.2	"
d	" "	39–50″	3	0.2	Partly decomposed pahoehoe lava
e	" "	30′	2	0.2	Pahoehoe lava
37–401a	Maui Substation	0–10″		0.7	Soil
37–401b	" "	10–20″		0.2	"
40–217a	Ewa, Oahu	0– 8″		3.2	Soil
40–217b	" "	8–12″		1.8	"
40–316a	Manoa, Oahu	0– 6″		.6	Soil
b	" "	6–18″		.4	"
c	" "	18–30″		.2	"
40–419a	Hamakua, Hawaii	0– 8″		1.1	Soil
40–419b	" "	8–20″		.7	"
40–216	Kona, Hawaii		3	0.2	Aa lava
40–284	University Farm		3	0.2	Pahoehoe lava

depth, the parent materials always having the smallest amounts. The value of 3 p.p.m. of total boron in the two samples of Hawaiian lavas is in agreement with analysis of other igneous rocks reported (8).

Distribution of total boron in surface soils:

A study of the total boron in twelve representative surface soils showed a variation from 8 to 56 p.p.m. The old uneroded soils from the high rainfall districts were found to contain the greatest amounts of total boron, while the heavily eroded soils, the young soils, and the soils from the dry districts contained low amounts of total boron. The high amounts of total boron found in certain soils may be attributed to one or more of the following factors: (1) Concentration as a result of intensive weathering, (2) concentration by the continuous action of plants bringing boron from the lower horizons, (3) the fixation of boron added to the soil by rain water containing sea salts.

Distribution of water-soluble boron in surface soils:

Water-soluble boron was determined on 33 representative surface soils. It was found to range from 0.4 to 3.2 p.p.m. In those soils where both total and water-soluble boron were determined, there was usually more water-soluble boron in the soils containing low amounts of total boron. One major exception was an eroded surface soil from upper Manoa Valley which contained 0.4 p.p.m. water-soluble boron and 8 p.p.m. total boron. In general, the old acid soils from the

high rainfall regions had the lowest amounts of water-soluble boron while the neutral soils from the dry areas had the highest.

Fig. 1 is a scatter diagram showing the relationship between soil pH and the amounts of water-soluble boron. This relationship is highly significant, the regression coefficient being 0.99 $\pm$ 0.17. However, this does not imply that the acidity of the soil caused the low amounts of available boron. Probably the soils which are acid have other properties which cause the low solubility of boron, measured by the procedure used.

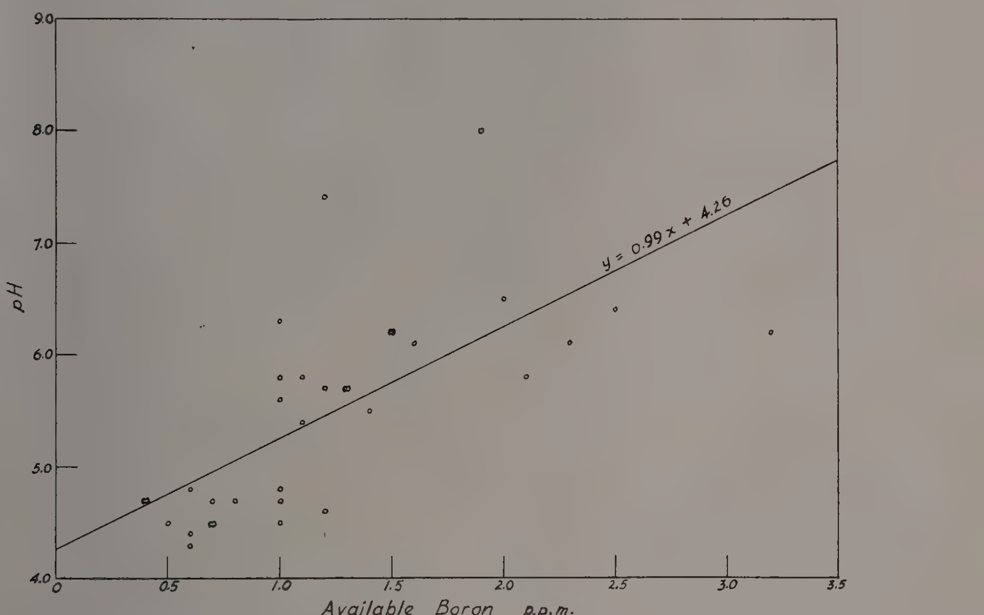

Fig. 1. Horizontal distribution of total and water-soluble boron in some Hawaiian soils.

Availability of Water-soluble Boron in Hawaiian Soils

A greenhouse investigation was undertaken to study the reactions of plants grown on Hawaiian soils having low amounts of water-soluble boron. Berger and Truog (2), working with Wisconsin soils have shown a good correlation between the water-soluble boron content of soils and the amounts of boron in the garden beets grown on them. They also found that the degree of black spot disease (a physiological disease caused by a lack of boron) was high in soils containing less than 0.7 p.p.m. of water-soluble boron. Ferguson and Wright (7) found that for the same soil type there was a relationship between the water-soluble boron of the soil and the amount of "apple cork disease."

The sunflower plant was selected as an indicator crop because its reactions to a boron deficiency have been described in detail (13). Three surface soils and one subsoil were selected because of their low water-soluble boron content. Each pot contained 400 gm. of soil and 5 sunflower seedlings. The treatments consisted of checks and 5 p.p.m. boron additions. All treatments were in triplicate. They were

watered with distilled water except at weekly intervals when 25 cc. of nutrient solution containing 2.5 gm. N, 1.5 gm. P, 3 gm. K, 3 gm. Ca, and 1 gm. Mg per liter were applied.

Four weeks after planting, definite boron deficiency symptoms were apparent on the plants in untreated soils 40–316a and 40–316b. On the other hand, plants growing on the same soils, but receiving an application of 5 p.p.m. of boron showed no evidence of boron deficiency. In Table II are given the dry weights and the boron concentrations of the sunflower tops after 6 weeks of growth. With the exception of the plants grown on soil 39–463 there is an agreement between the composition of the plants and the water-soluble boron in the soil. The relation between plant weights and soil boron appears to be only a general trend. Soil 39–463 was very acid and infertile; consequently, factors other than boron deficiency probably limited plant growth and accounted for the lack of response to the low boron concentration of the soil.

TABLE II

WATER-SOLUBLE SOIL BORON IN RELATION TO THE GROWTH, DEFICIENCY SYMPTOMS AND BORON CONTENT OF SUNFLOWER SEEDLINGS

Soil No.	Available boron in soil	Boron added to soil	Average dry weight of tops	Boron in tops	Boron deficiency symptoms
	p.p.m.	p.p.m.	gms.	p.p.m.	
39–482	0.7	0	13.4	16	None
39–482	0.7	5	14.5	52	None
40–316a (0–6″)	0.6	0	12.3	11	Apparent
40–316a (0–6″)	0.6	5	15.1	34	None
40–316b (6–18″)	0.4	0	12.4	8	Apparent
40–316b (6–18″)	0.4	5	15.6	35	None
39–463	0.5	0	9.3	12	None
39–463	0.5	5	10.0	40	None

TABLE III

CONCENTRATIONS OF BORON FOUND IN HAWAIIAN WELL AND SEA WATERS

Source	Description	Boron p.p.m.
Koko Head	Well water	0.7
Waianae	" "	0.09
Ewa	" "	0.18
University Campus	Tap water	0.03
Near Shore	Sea water	3.6

Boron Fixation by Hawaiian Soils

When a solution containing boric acid, or borax, is brought in contact with certain soils, there is a tendency for the soil to fix or reduce the boron concentration of the solution. Eaton and Wilcox (6) have shown that the fixation of boron is of importance when irrigation waters contain large amounts of boron. For example, lemon trees grown on high boron-fixing soils showed less injury due to the application of high boron irrigation waters than those grown on soils with a

low fixing power. Since the presence of toxic quantities of boron in a soil is most likely to occur as a result of using irrigation waters containing this element, it was of interest to examine certain Hawaiian waters. Table III gives the concentration of boron found in four well waters and in a sample of sea water collected near the shore. The sea water sample was lower in boron than the reported value of 4.5 for the Pacific (9) and 4.75 for the North Atlantic (11). The high amount of boron in the well water at Koko Head was undoubtedly a result of the mixing of sea and fresh water. The boron content of the other well waters was low in comparison with many of the natural waters found in California (12).

Some indications of the fixation of boron by Hawaiian soils were obtained from a study with an alluvial soil from Ewa (39–481) and a residual soil from mauka fields in Waipio (39–463). Twenty-gram soil samples and 100 ml. of solutions containing 0.25, 0.50 and 1.00 p.p.m. boron, as boric acid, were shaken in an end-over-end shaking machine for an hour. These suspensions were allowed to stand for 3 days and the boron concentrations of the supernatant liquids determined. The data obtained from these determinations are given in Table IV. It can be seen that the Waipio soil, which had a low level of water-soluble boron, fixed appreciable amounts of boron from a solution containing as little as 0.25 p.p.m.

TABLE IV

FIXATION OF BORON FROM SOLUTIONS OF VARIOUS CONCENTRATION

Soil	Soil pH	Boron concentration initial solution	Boron concentration final solution	Decrease in concentration of original solution
		p.p.m.	p.p.m.	per cent
Waipio	4.2	0	0.08	..
39–463		0.25	0.20	20
		0.50	0.32	36
		1.00	0.68	32
Ewa	8.0	0	0.18	..
39–481		0.25	0.25	0
		0.50	0.32	36
		1.00	0.55	45

TABLE V

THE EFFECT OF LIMING ON THE AVAILABILITY AND TOXICITY OF BORON

Liming Treatment	Boron added	Dry weight of tops	Boron concentration in tops	Total boron found in tops	Water-soluble boron in soil after harvest	Comments
	p.p.m.	gms.	p.p.m.	mgm.	p.p.m.	
Unlimed	0	14.7	28	0.41	0.5	Normal plants
Limed	0	19.0	23	0.44	0.4	Slight deficiency symptoms
Unlimed	2.5	14.9	100	1.49		Normal plants
Limed	2.5	20.0	92	1.84		Normal plants
Unlimed	10	15.8	200	3.16		Slight boron injury
Limed	10	19.8	150	2.97		Normal plants
Unlimed	25	16.1	360	5.80	4.2	Severe boron injury
Limed	25	21.6	250	5.40	5.3	Slight boron injury

On the other hand, the Ewa soil, which had a high level of water-soluble boron, fixed no boron from the lowest concentration; but, in contact with the highest concentration, it fixed more boron than the Waipio soil. The magnitude of fixation exhibited by these soils is of the same order as that reported by Eaton and Wilcox (6) for California soils. These workers have also shown that if a soil is dried while in contact with a boric acid solution an even greater fixation occurs. This would more nearly resemble field conditions.

Certain evidence has been presented by Naftel (10) and others showing that liming the soil causes boron starvation in some plants. Cook and Millar (5) effectively masked crop injury from excessive applications of boron by applying calcium and magnesium carbonates. There is no evidence, however, that calcium and magnesium carbonates fix boron in the soil.

An acid pineapple soil was selected for a pot series to show the effect of liming on boron availability and toxicity. The series included limed and unlimed soils which in one instance had received no boron and in others had received 2.5, 10, and 25 p.p.m. of boron as boric acid. All pots contained a kilogram of soil. The limed pots received 5 grams of C.P. calcium carbonate. All treatments were in triplicate, three sunflower seedlings were allowed to grow in each pot, and were harvested at the end of 6 weeks. The plants received distilled water and at weekly intervals 25 ml. of the nutrient solution previously described.

At the time of harvest the plants growing in the limed soil to which no boron had been added showed slight but definite boron deficiency symptoms, while the plants in the corresponding unlimed soil were normal. The plants grown on the limed soils which received 10 and 25 p.p.m. of boron showed no injury and slight injury, respectively, from the excessive amounts of boron. But, with the unlimed soils the injury was slight for the 10 p.p.m. and severe for the 25 p.p.m. applications. These observations seem to indicate that liming decreased the availability of the boron to the plant.

The dry weights of the sunflower plants (Table V) show in all instances an increased growth resulting from liming. There is no evidence that the boron treatment either increased or decreased the growth. The apparent injury to the leaves reported above was not reflected in the dry weights.

The boron concentration in the tops of the plants growing in the limed soils was always less than the corresponding unlimed ones (see Table V). However there was no important difference in the total amount of boron in the limed and unlimed plants. This indicates that the lime did not actually decrease the availability of boron in the soil, but did affect the actual concentration in the plant by promoting increased growth.

The amounts of water-soluble boron remaining in the soil treated with 25 p.p.m. of boron indicate considerable fixation of boron by the soil.

Distribution of Boron in Various Hawaiian Agricultural Crops

The amounts and distribution of boron in various species of plants vary greatly. Furthermore, the total absorption of boron by different species of plants in the same soil or culture solution may not be the same. Scofield and Wilcox (12) report a relationship between the boron content of orange tree leaves and that

of the water supplied to them. Several boron analyses of various crops and plant parts are presented herein only as a matter of record. Their interpretation at present is of only general interest; however, they may become of interest if at some time it is advisable to continue this investigation of the role of boron in Hawaiian agriculture.

Sugar cane: Some indications of the amount and distribution of boron in the sugar cane plant were obtained from analyzing samples grown at the Kailua and Waipio substations of the Experiment Station, H.S.P.A., as well as in water cultures. These samples* from Waipio and Kailua were from 15-month old plant crops of 31–1389. The segregation into the various plant parts is the same as described by Clements (3). Two sets of water-culture samples were analyzed of which one was grown in a complete nutrient solution, while the other was grown in a minus-boron solution. These are the same plants as those reported on by Clements, Martin and Moriguchi (4).

The results of the boron analysis are shown in Table VI. Like most of the Gramineae, the sugar cane plant contains relatively low concentrations of boron, the highest concentrations being found in the meristem, elongating cane and leaf blades. In the absence of sufficient boron these parts also show the greatest decrease in concentration from the normal. The lower internodes, or millable cane, contain very small amounts of boron. It is estimated that a normal crop removes from the field less than 0.5 pound of boron per acre.

Pineapples: The distribution of boron was determined in two sets of pineapple plants, one from Oahu and the other from Kauai. The Oahu plants were grown in a soil containing 1.0 p.p.m. of water-soluble boron, whereas the Kauai pineapple soil cointained only 0.4 p.p.m. Both sets of plants were divided into groups of comparable physiological age.

The boron analysis of the pineapple plant samples is presented in Table VII.

TABLE VI

DISTRIBUTION OF BORON (P.P.M. IN DRIED TISSUE) IN SUGAR CANE GROWN AT KAILUA, WAIPIO, AND IN NUTRIENT SOLUTIONS

Plant part	At Kailua substation	At Waipio substation	In complete nutrient solution	In Minus—boron nutrient solution
Spindle cluster	3.2	4.8	4.9	1.3
Leaf blades, elongating cane	3.6	3.5	11.0	2.4
" " green-leaf cane	3.2	7.0	11.0	
Leaf sheaths, elongating cane	1.9	2.1	3.6	1.4
" " green-leaf cane	1.6	1.6	3.2	
Meristem	9.5	9.5	9.0	3.1
Elongating cane	7.0	5.5		
Green-leaf cane	1.5	1.6	2.4	
Top internodes	1.0	1.0	1.6	1.0
Next three internodes	1.2	1.1	1.1	1.0
" " "	1.0	0.8	0.9	.5
" " "	0.8	0.6	0.7	
All other internodes	<0.5	<0.5		
Water-soluble boron in soil	0.8	1.8		

* These samples were supplied through the courtesy of the Division of Plant Physiology.

TABLE VII

THE DISTRIBUTION OF BORON IN PINEAPPLE PLANTS
(p.p.m. in dried tissue)

OAHU PLANTS Plant part	Boron content	KAUAI PLANTS Plant part	boron content
	p.p.m.		p.p.m.
"C" Leaves, white basal	7	"C" Leaves, white basal	4
" " central	18	" " central and tips	15
" " tips	36		
"D" Leaves, white basal	10		
" " central	17		
" " tips	24		
"E" Leaves, white basal	7	"D, E and F" Leaves, white basal	7.0
" " central	9	"D, E and F" Leaves, central and tips	9.0
" " tips	13		
"F" Leaves	6		
Growing point	9	Growing point	5.5
Water-soluble boron in soil	1.0	Water-soluble boron in soil	0.4

"C"—Fully grown leaves at an angle greater than 45° from vertical.
"D"—Leaves at an angle of 30–45° from vertical.
"E"—Leaves more than a foot in length and less than 30° from vertical.
"F"—Remaining leaves and leaf primordia.

TABLE VIII

BORON CONTENT OF MISCELLANEOUS CROPS GROWN WITH AND WITHOUT THE USE OF BORON AS A FERTILIZER.
(p.p.m. in dried tissue)

Plant	Plant part	Boron content	Comments
		p.p.m.	
Radish	Tops	34	Pot culture—0.7 p.p.m. H_2O soluble soil B
"	Roots	25	" " " " " "
"	Tops	72	" " " " " " 3 p.p.m. B added
"	Roots	30	" " " " " " " " "
Beet (table)	Tops	32	" " " " " "
" "	"	20	" " " " " " $CaCO_3$ added
" "	"	73	" " " " " " 3 p.p.m. B added
Tomato	Tops	14	" " " " " "
"	"	26	" " " " " " 3 p.p.m. B added
Coffee tree	Leaves (young)	52	1.0 p.p.m. H_2O soluble soil B
"	" (old)	76	" " " "
"	Leaves (young)	80	1.0 p.p.m. H_2O soluble soil B trees fertilized with B
"	" (old)	156	" " " " " " " "

These data show the highest concentration of boron to be in the older plant parts such as the leaf tips. The meristematic regions, that is, white basal leaf tissue and the growing points, were comparatively low in boron. The plants growing in the low boron soil contained less boron than the ones from the soil with high boron. The older leaf parts (tips and central sections) showed the most marked decrease in concentration due to low amount of water-soluble boron.

Miscellaneous crops: Radish, beet and tomato seedlings were grown in a pot culture series, using the same soil (Manoa 39–482), both with and without the additions of boron. The boron content of the plant materials harvested from this experiment was determined and the results shown in Table VIII. These data show the radish and beet tops to have about the same concentration of boron. The tomato tops, on the other hand, showed a considerably lower concentration. The addition of 3 p.p.m. of boron to the soil approximately doubled the concentration of boron in the tops of all the three plants.

Leaf samples were collected from coffee trees growing in Kona, Hawaii. Some of the trees had received 6 pounds of boron per acre annually for two years prior to sampling. The boron analysis of these samples is given in Table VIII. The young leaves were approximately 3 months old at the time of sampling, while the old leaves were a year older than the young ones. These results show a definite accumulation of boron in the older leaves. There was a marked increase in the amounts of boron in the leaves of the trees fertilized with boron.

Summary

This paper on the boron status of Hawaiian soils gives consideration to: (a) The distribution of total and water-soluble boron, (b) the availability of water-soluble boron, (c) the fixation of boron, and (d) the boron content of various agricultural crops. The results may be summarized as follows:

(1) The total boron was found to be highest in surface soils—4 to 56 p.p.m. The old uneroded soils from regions of heavy rainfall have the most total boron.

(2) The water-soluble boron was highest in surface soils and varied from 0.4 to 3.2 p.p.m. Generally, the soils with high total boron had a low water-soluble boron content. A significant relationship was found between soil pH and water-soluble boron content.

(3) It was demonstrated that certain Hawaiian soils have the property of fixing boron from dilute solutions of boric acid.

(4) The distribution of boron in the various organs of sugar cane and pine-apple plants was determined and presented. A normal crop of sugar cane removes from the soil less than 0.5 pound of boron per acre.

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Rainfall Evaluation as an Aid to Irrigation Interval Control

By J. A. Swezey

Rainfall can range in effect from a menace to life and property, when it is of cloudburst proportions, to a mere insignificant and ignored "trace" on the records of a weather station. Depending upon the moisture content of the soil just prior to a rain, the amount and to a certain extent the intensity of the precipitation, rainfall can be as great a boon to agricultural projects as a full or partial irrigation.

The evaluation of normal amounts of rainfall as supplementary irrigations on Hawaiian sugar cane lands has been for years attained by individual judgment, and has been influenced largely by personal considerations. In general, the estimated degree of credit allowed any rainfall was on the conservative side of not attempting to claim as much benefit for the rain as it may actually have been worth. This was never satisfactory to the sugar planter, for he would have liked to improve irrigation efficiency by claiming more nearly the full credit for a rain, as well as to have been freed of the uncertainty attached to a conjectured estimate of the rain's effectiveness.

In recent years studies of soil moisture and cane growth relationships have indicated that a program of regular, routine soil-moisture observations could be expected to provide information relative to the length of the irrigation interval, *i.e.,* the elapsed time between successive irrigations which would furnish the cane plant with water at the most efficient frequencies on a basis of the commercial product (3), (6), (7). Such a soil-moisture observation program would also reveal directly the effect of any rainfall upon the extension of the irrigation interval, with a resultant increase in efficiency.

The late Dr. U. K. Das, in 1936 (1), suggested the use of day-degrees as a measure of the irrigation requirements of the sugar cane plant. In developing this proposed utilization of day-degrees, he recognized rainfall as a factor which would have to be evaluated in order to properly operate an irrigation control based on day-degrees. We quote from Dr. Das' paper:

"How to adjust for rainfall? In the arid or semi-arid districts like Waianae or Ewa an inch of rainfall may be considered as equal to one-tenth of an irrigation (*i.e.,* ten per cent of the area irrigated). This value may be somewhat different in different places. However, once we have decided from experimental or observational data what value to give to rainfall, we can take that into account in determining when to apply the next irrigation. In general it may be advisable to underestimate rather than overestimate the value of scattered showers."

Preliminary Attempts

In September 1939 at Waipio a rain of 1.54 inches in a 24-hour period fell on the 32 plots of Experiment 104-I. These plots had a considerable variation in their soil moisture contents at the start of the rain. An opportunity was thus afforded to analyze the effect of this rain toward replenishing soil moistures under the various existing conditions. From such an analysis a set of curves, one for each 0.1-inch increment of rainfall, was derived which would correct an irrigation inter-

val for such rainfall as might occur at any time between scheduled irrigations. The elapsing interval and the correction for rainfall were expressed in day-degrees, so as to take advantage of this suggested method of gauging intervals. The correction was to be deducted from the elapsed interval.

These corrections were offered in the forms of curves and tables to a number of plantations for trial (4). It was recognized that, being based on the effects of a single rain, the corrections were subject to a probable wide margin of error, and that they would suffice only as a partial help in allowing for rain. The collaborators were so advised.

During 1940 a study of available cane growth, soil moisture, rainfall, and day-degree records from Experiment 138-I at Waialua resulted in the derivation of a second set of curves and tables for rainfall evaluation (5). These were released in January 1941 in the belief that they were developed on a much sounder basis than the first tables, since many observations were used of various amounts of rain falling on soil with a wide range of moisture contents prior to each rain. These tables seemed quite acceptable for some conditions, but on the rainy side of Kauai they appeared to account inadequately for continuous small rains.

In March 1941 a study of data from Experiment 104-I harvested early in 1941 at Waipio produced a third set of adjustments for rainfall. These were discussed before several seminar groups composed respectively of the staff of the Experiment Station and the staffs of various plantations on Oahu and Kauai. It was hoped that the discussions would reveal any errors or omissions, inherent in the new tables, and would indicate from the opinion of field experience the necessary rectifications. The seminars proved to be most helpful, especially those conducted at individual plantations where a variety of specific problems (soil depth, moisture-holding capacity, wind effect, cane variety, etc.) was brought to our attention. As was expected, the new adjustments were found to be fallible in some respects, even within the rough limits of field usage. All who participated in the seminars, however, believed that the tables could be revised to account for the suggested weaknesses. One major criticism was that they were not properly applicable to shallow soils. Another objection was that there was a discrepancy in the amount of day-degrees from irrigation to wilting point between the second and the third set of curves. Due to these objections and others of a minor nature this third set of curves was not released.

It should be stated that each of these curves was used in turn at Waipio with no disastrous results. However, there were infrequent rains of small consequence during their two-year use.

Evolution of Present Rain Evaluation Tables

Personal discussions with mainland investigators and papers offered at the June 1941 meetings of the Western Society of Soil Science (9), together with a reconsideration of the data in Experiments 138-I and 104-I, have resulted in a revised perspective in approaching the problem of adjusting irrigation intervals for rainfall. This paper will present a group of adjustments based on this latest interpretation of the relationships between sugar production, soil moisture, and the value of rainfall, and will describe how these new adjustments are used at Waipio to regulate the scheduled irrigation intervals in accordance with rainfall received.

The first three sets of rainfall tables which were devised were based on a single depth of root zone (34 inches), and on a single 8 per cent available soil-moisture capacity (8 per cent from maximum field capacity to first wilting point), and using H 109 cane. Seminar discussions indicated that a means of accounting for a number of different soil conditions and situations would be necessary to allow satisfactorily for rains according to the general method proposed with the adjustment tables. In order to avoid presenting too many tables, which by their bulkiness would prove too cumbersome for practical field use, it was decided to devise a table of adjustments for each of three levels (high, medium, and low) of the two factors of soil conditions involved. Therefore, nine specific tables are presented on the following bases:

Table no.	Approximate depth of root zone (inches)	Range of moisture equivalent (per cent)	Average corresponding available soil moisture (P_{fwp}) (per cent)
I	34	36–50	11
II	34	25–36	8
III	34	12–25	5
IV	23	36–50	11
V	23	25–36	8
VI	23	12–25	5
VII	11	36–50	11
VIII	11	25–36	8
IX	11	12–25	5

Determination of Soil-Moisture Extraction Curves

The first step necessary in deriving the tables was to find how many day-degrees should be expected to accumulate, *with no interference from rainfall,* between the day of irrigation and the day on which the "first permanent wilting point" was reached in the soil moisture. To determine this amount of day-degrees, detailed studies of the rates of soil moisture extraction in Experiment 104-I (Waipio) were analyzed statistically. Fig. 1 shows how the rates of soil moisture extraction were determined. The case used is from actual observations in Experiment 104-I, Plot 2-A.

The plot was irrigated on June 14 and a series of soil moisture observations from June 17 to June 24 inclusive produced an irregular extraction curve. During the day ending at 6 a. m., June 25, a rain of 0.21 inch was received. A series of samples taken from June 25 to July 3 inclusive also showed some irregularity, but all samples were at or below the wilting point. H 109 cane growth is seen to have proceeded at a rapid rate from June 14 to June 27 inclusive, after which the growth rate was retarded. Another irrigation was applied on July 5, and was followed by an increase in the rate of cane growth.

The single irrigation cycle, or interval, thus described may be interpreted as follows:

We have laid a straight edge on the soil-moisture observations of June 17 to 24, and moved it about to obtain the best fit to the plotted points. A dashed line is drawn to define this fit, and it represents the probable rate of extracting moisture from this soil by the cane crop. There is no reason to suspect that the extraction rate between June 14 and 17 would be materially different from the rate obtained

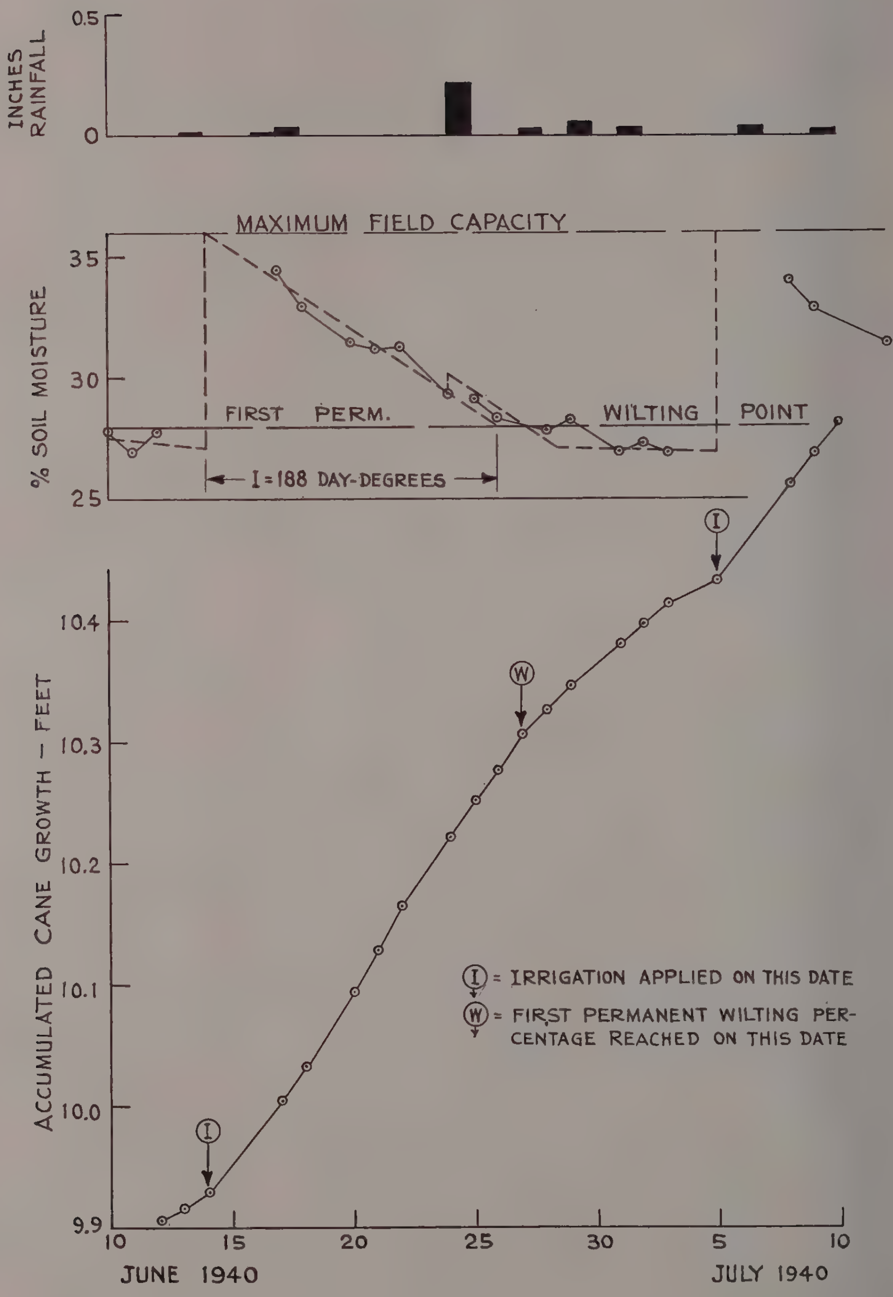


Fig. 1. Sample of graphical records of soil moisture, H 109 cane growth, and rainfall data for Plot 2-A of Waipio Experiment 104-I. (This shows the method of determining rates of soil-moisture extraction in terms of day-degrees.)

by the observations taken between June 17 and 24. Therefore we have extended the dashed line to the left to intersect the maximum field capacity on June 14, the day of irrigation. Likewise this line is extended to the right to intersect the first wilting point on June 26. In other words, if the rate of soil-moisture extraction, which is indicated by soil samples to have prevailed between June 17 and 24, is considered to be representative of the probable uninterrupted period of time from field capacity to the wilting point, then this period was from June 14 to June 26. The weather data showed that 188 day-degrees were accumulated between these dates. This period of extraction of readily available soil moisture is termed "I." Similar interpretations were made for all possible cases to be found in the experiment and a large number of values in day-degrees were obtained for "I."

Notice that our interpretation of the soil-moisture data shows that the wilting point was actually reached on June 27, not on the 26th. This is verified by the slowing of the cane growth after June 27, and is without doubt due to the 0.21 inch of rain falling between June 24 and 25.

A statistical analysis of many rates of soil-moisture extraction thus determined gave the following results:

In Experiment 104-I at Waipio it was found that 808 observations of rates of soil-moisture extraction by the sugar cane plant gave a true mean of 175.9 day-degrees from the date of irrigation to the date on which soil moisture would be expected to reach the first permanent wilting point. The probable error of this mean was ±0.77 day-degree, and the probable error of any single observation was ±21.8 day-degrees. The probable error of a single observation is the important figure to inspect. In experiment 104-I it is 12.4 per cent of the mean. The expected error of a single interval that might be applied is therefore within the variability of field practice in applying irrigation intervals. For example, if a 15-day interval is scheduled for a field and the water is applied on the 17th day, or two days late, the irrigation is late by 13.4 per cent of the scheduled interval. In many actual cases irrigations are even more than two days late, due to any of a number of causes. Hence the interval of 175.9 day-degrees might be considered satisfactorily reliable as a basis upon which to start developing curves for interval adjustments.

For the benefit of those readers who are mathematically inclined, it will now be necessary to inflict some symbols and calculations on other readers, in order that the derivation of these adjustments will be clearly understandable.

The soil of Experiment 104-I is identical with the conditions cited for Interval Adjustment Table II, *i.e.*, 8 per cent soil moisture above the first wilting point available to the cane in a 34-inch deep root zone.

Referring to the nomenclature in Appendix I, and using the Equation No. 2 which expresses the manner in which soil is saturated by water applied on the surface, the following relationships are found for this soil:

$MFC = 36\%$
$FWP = 28\%$
$V = 1.1$
$d = 34$ inches
$I = 175.9$ day-degrees
$R = ?$

$$P_{fwp} = \frac{MFC - FWP}{100} = \frac{8\%}{100} = 0.08$$

$$D = P_{fwp} \times V \times d = 0.08 \times 1.1 \times 34 = 2.99 \text{ inches of water.}$$

Equation No. 3 gives the soil-moisture extraction rate:

$$R = \frac{I}{D} = \frac{175.9}{2.99} = 58.8 \text{ day-degrees per inch of water.}$$

The significance of the value of R is that when 58.8 day-degrees have been accumulated from the date of an irrigation, it can be expected that 1 acre-inch per acre of water has been taken from the soil by the cane crop.

The ideal soil-moisture extraction curve for the Waipio soil appears in Fig. 2. This shows a straight sloping line descending from 8 per cent soil moisture available at 0 elapsed day-degrees to 0 per cent available moisture at first permanent wilting point, which occurs at 176 elapsed day-degrees.

The soil-moisture extraction curves for the other 8 combinations of soil depths and available moisture capacities were derived as follows:

Combining the equations for D and R given above, we have:

$$R = I/D = \frac{I}{P_{fwp} \times V \times d}$$ in which R is presumed to have the same value in all cases (58.8 day-degrees per inch of water).

Therefore: $I = R \times P_{fwp} \times V \times d$

This equation was used, then, for the remaining 8 cases:

Case I:

$P_{fwp} = 11\% = 0.11$ — $R = 58.8$
$d = 34$ inches — $V = 1.1$
$I = 58.8 \times 0.11 \times 1.1 \times 34 = 241.9$ day-degrees. — $I = ?$

Case II:

This was obtained by measurements in the field (Expt. 104-I) and has been given above, *i.e.*, $I = 175.9$ day-degrees.

Case III:

$P_{fwp} = 5\% = 0.05$ — $R = 58.8$
$d = 34$ inches — $V = 1.1$
$I = 58.8 \times 0.05 \times 1.1 \times 34 = 110.0$ day-degrees. — $I = ?$

Case IV:

$P_{fwp} = 11\%$ — $R = 58.8$
$d = 23$ inches — $V = 1.1$
$I = 58.8 \times 0.11 \times 1.1 \times 23 = 163.6$ day-degrees. — $I = ?$

Case V:

$P_{fwp} = 8\%$ — $R = 58.8$
$d = 23$ inches — $I = ?$
$I = 58.8 \times 0.08 \times 1.1 \times 23 = 119.0$ day-degrees. — $V = 1.1$

Case VI:

$P_{fwp} = 5\%$ — $R = 58.8$
$d = 23$ inches — $V = 1.1$
$I = 58.8 \times 0.05 \times 1.1 \times 23 = 74.4$ day-degrees. — $I = ?$

Case VII:

$P_{fwp} = 11\%$ — $R = 58.8$
$d = 11$ inches — $V = 1.1$
$I = 58.8 \times 0.11 \times 1.1 \times 11 = 78.3$ day-degrees. — $I = ?$

Case VIII:

$P_{fwp} = 8\%$ — $R = 58.8$
$d = 11$ inches — $V = 1.1$
$I = 58.8 \times 0.08 \times 1.1 \times 11 = 56.9$ day-degrees. — $I = ?$

Case IX:

$P_{fwp} = 5\%$ — $R = 58.8$
$d = 11$ inches — $V = 1.1$
$I = 58.8 \times 0.05 \times 1.1 \times 11 = 35.6$ day-degrees. — $I = ?$

It is interesting to compare the rate of soil-moisture extraction by H 109 cane from Experiment 104-I at Waipio with that found in Experiment 138-I at Waialua. In the latter experiment it was found that 986 observations of rates of soil-moisture extraction gave a true mean of 131.0 day-degrees between the date of irrigation and the date on which soil moisture reached the first permanent wilting point. The probable error of this mean was ±0.59 day-degree, and the probable error of any single observation was ±18.4 day-degrees.

The value for R in the Waialua test is found to be 62.1, as follows:

$$P_{fwp} = \frac{MFC - FWP}{100} = \frac{8\%}{100} = 0.08 \qquad I = 131.0 \text{ day-degrees}$$

$$d = 24 \text{ inches} \qquad V = 1.1$$

$$R = ?$$

$$R = I/D = \frac{I}{P_{fwp} \times V \times d} = \frac{131.0}{0.08 \times 1.1 \times 24} = 62.1 \text{ day-degrees per inch of water extracted.}$$

This is close to the value (58.8) found at Waipio, and tends to indicate that the rate of extraction of soil moisture in two widely separated localities can be measured by the common index—the day-degree. True, this is only one comparison, but it should serve to stimulate interest toward obtaining additional comparisons.

The reason why there is a difference between Waialua and Waipio in the number of day-degrees between an irrigation and the date on which soil moisture reached the first wilting point is that at Waipio there was a root zone at least 34 inches in depth, whereas in the Waialua experiment we are certain that a hard pan limited the effective root zone to a depth of about 24 inches. It is only natural that the wilting point would be reached sooner in the Waialua experiment, there being less total water per acre available after irrigation due to the shallower root zone. Previously we had neglected to consider the difference in depth of root zones between these two sets of data.

From the values of P_{fwp} and the corresponding values of I calculated above, soil-moisture extraction curves for our 9 cases were obtained and plotted in Figs. 3 through 11; see Appendix II.

On all of these graphs showing the soil-moisture extraction, it is seen that the curves extend beyond the first permanent wilting point to a soil-moisture value 2 per cent below the first permanent wilting point, and remain constant from there on. This lower level of moisture is termed the "ultimate permanent wilting point." It is used in these graphs because the soil-moisture data obtained from both experiments mentioned above show that the cane plant actually extracted from two to four per cent of moisture below the first permanent wilting point.

Wilting Point vs. Wilting Range

Reference to two permanent wilting points, first and ultimate, may be somewhat confusing to the reader, since in recent years there has been an increasing tendency in Hawaii to apply only the one term "permanent wilting point or percentage" to designate the lower limit of soil moisture available to the cane plant. An explanation, and revision of our ideas regarding wilting is necessary at this stage of our soil-moisture investigations.

We have come to presume that the "permanent wilting point" of a given soil is at a specific percentage, and have stressed this amount as the lower limit of soil moisture readily available to the plant for the promotion of a normal rate of growth. Even though the first decrease in growth rate was relatively slight when this specific point was reached, and further moisture was extracted before the growth rate became severely handicapped, still the reduction in the rate of elongation was accepted as a commercial loss. Hence, the probable existence of a wilting range was subordinated to the concept of that moisture content at which the first departure from rapid growth occurred as being the all-important and critical limit of availability. It is true that our literature does mention a wilting zone or range, yet the tenor of these comments definitely attaches major importance to the upper edge of that zone as more critical than the lower.

Subsequent experiments, well-replicated and carefully operated, have shown that soil moisture is actually extracted by the H 109 cane to a level which is 2 to 4 per cent below that formerly described as the permanent wilting percentage. Observations in these experiments indicated that except for a reduction of growth rate, no visible distress was manifested by the cane during the time this additional 2 to 4 per cent moisture was being extracted. A reduction of cane tonnage resulted from repeatedly withholding irrigations until some time after "permanent wilting percentage" was passed, but this was no commercial loss, since the sugar yield was not reduced and the cost of irrigation was lessened (6), (7). It would seem that allowing soil moisture to fall below the "permanent wilting percentage" to a still lower limit, at which soil moisture became in fact totally unavailable, was not destructive to the commercial yield from the field.

Apparently, therefore, the "permanent wilting percentage" as we have used it is what the mainland investigators in recent years have termed the "first permanent wilting point." Some physiological reaction in the cane plant undoubtedly commences when soil moisture reaches this level, but the plant continues to obtain additional moisture from soil that is depleted to a still lower level, which these same investigators term the "ultimate permanent wilting point," and at which soil moisture then becomes unavailable. Thereafter, an injurious effect on the plant's physiological processes develops with increasingly acute severity unless soil moisture is replenished within a reasonable time (2), (8). Our experiments have given some indications of the length of this time.

The opinion of mainland soil scientists regarding wilting is capably reviewed in recent papers by J. R. Furr and C. A. Taylor of the U. S. D. A. at Pomona, California (2), (8). In discussions with Drs. Furr, F. J. Veihmeyer and A. H. Hendrickson of the University of California at Davis, California, and G. E. P. Smith of the University of Arizona, this opinion was stated personally. It may be summarized briefly as follows:

(1) Wilting does not occur necessarily at a definite precise level of per cent soil moisture. The above investigators invariably refer to a "wilting range."

(2) The first, but more or less unimportant, signs of wilt appear at the "first permanent wilting point."

(3) The "ultimate permanent wilting point" is the lowest limit of soil moisture extractable by the plant, and is the critical moisture content relative to the plant's physiology.

Derivation of Interval Adjustment Tables From Soil-Moisture Extraction Curves

In our consideration of the problems of the moisture conditions of the soil and the reactions of the cane to these conditions, we have not lost sight of the fact that even after moisture has been extracted to the ultimate wilting point in the surface root zone, there are still a number of long tap roots which probably supply the plant with some moisture for an additional period of time. This moisture is of partial benefit to the plant, and undoubtedly can complicate the evaluation of the relationships of rainfall, soil moisture, and plant reaction, but for the present, practical considerations dictate that it be disregarded.

Using the soil-moisture extraction curves, it is possible to obtain curves to adjust the irrigation interval for various amounts of rain. Actually the adjustments are supplied in tabular form, but the method of computing the tabular values will be explained graphically using Case II, the Waipio soil with 8 per cent soil moisture (P_{fwp}) available to the cane, and a 34-inch depth of root zone.

In this case, and all others, the per cent moisture available to the plant is to be understood to mean the difference in per cent moisture between maximum field capacity and the first wilting point. The reason for this is that the first wilting point can be detected far more readily in the field than the ultimate wilting point. The first wilting point, having been checked for number of day-degrees after irrigation, determined the rate of soil-moisture extraction (R). The ultimate permanent wilting point in terms of day-degrees could then be fixed. The —2.0 per cent avail-

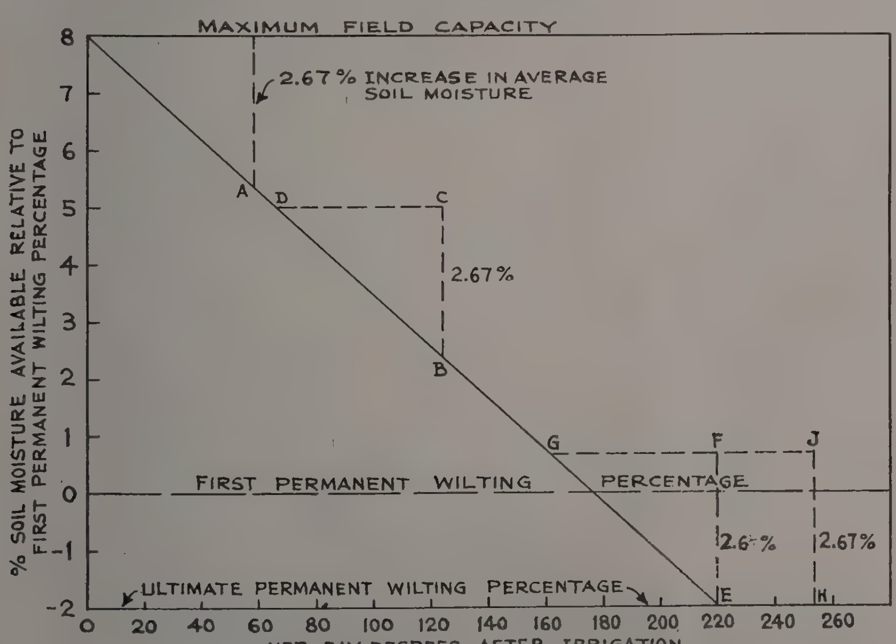


Fig. 2. Ideal soil-moisture extraction curve for H 109 cane at Waipio. (This shows method of obtaining tabular values for the effect of 1.0 inch of rain.)

able moisture, appearing on Fig. 2, is actually available to the plant. It, of course, represents the wilting range.

Fig. 2 shows the effects of 1.0 inch of rain superimposed at various points after irrigation on the ideal soil-moisture extraction curve for the Waipio soil. An inch of rain falling on this soil at any time will result in a 2.67 per cent increase in the average moisture content of the 34-inch depth of soil. This is very simply explained as follows:

Since this soil can hold 8 per cent of soil moisture between field capacity and first wilting point, and since, as shown above, this corresponds to a 3.00-inch depth of water applied on the surface, then 1 inch of water would correspond to

$$\tfrac{1}{3} \times 8\% = 2.67\%$$

A more detailed demonstration, requiring several pages of computations, would show the same figure.

Suppose that an inch of rain starts to fall when 58 day-degrees have been accumulated from the time of the last irrigation. The soil moisture is 2.67 per cent below *MFC* at the start of the rain, *i.e.,* at 58 day-degrees. (This is indicated by point *A* on the extraction curve.) Obviously this rain will increase the soil moisture to Field Capacity, which essentially sets the irrigation interval back to "0" on the day-degree scale. If this rain had occurred sooner, it would have had the same effect on the interval—set it back to "0," since if soil moisture is less than 2.67 per cent below *MFC*, the inch of rain is more than enough to replenish the soil and the superfluous water received is lost by deep percolation.

An inch of rain occurring at 124 day-degrees after irrigation would fall on soil with a moisture content of 2.33 per cent above the first wilting point (Point *B*). This one-inch rain would increase the moisture by 2.67 per cent, or to 5 per cent above the first wilting point (Point *C*). This is the same as retreating on the extraction curve to Point *D* which is at 66 day-degrees after irrigation. The irrigation interval is thus setback by the 1.0-inch rain from 124 to 66 day-degrees.

If the inch of rain fell on soil with a moisture content just at the ultimate wilting point (Point *E*, at 220 day-degrees after irrigation), the soil moisture would be increased from —2.0 per cent to 0.67 per cent above the first wilting point (Point *F*). This is equivalent to retreating on the extraction curve to Point *G* which is at 162 day-degrees after irrigation. The 1.0-inch rain therefore set the interval back from 220 to 162 day-degrees.

Should the inch of rain occur when the interval had reached a total of over 220 day-degrees, say 254 at Point *H*, the rain would have the same effect as in the previous paragraph; the average soil moisture would be increased to 0.67 per cent above the first wilting point (to *J*) which is equivalent to retreating on the extraction curve to *G* at 162 day-degrees after irrigation.

These examples, then, provide a correction table for one inch of rain. An inch of rain falling at any time up to 58 day-degrees after irrigation, will result in setting the interval back to "0" day-degrees. A rain of one inch occurring anywhere between 58 and 220 day-degrees, it will be noticed, set the interval back by the same amount—58 day-degrees. A one inch rain coming at or after 220 day-degrees will set the interval back to 162 day-degrees.

It should be obvious that a tenth of an inch of rain will set the interval back by one tenth the number of day-degrees as will a one-inch rain.

In setting up a table of adjustments for rains of 0.1-inch differentials the adjustments would be cumbersome and would not be spaced equally from irrigation to the ultimate wilting point if strict adherence were maintained in using 58 day-degrees per inch of rain for the value of R. Note that for 0.1 inch of rain, R would become 5.8 day-degrees. For the sake of simplicity and uniformity in tabular values we have taken $R = 60$ day-degrees, which becomes 6.0 day-degrees for each 0.1 inch of rain. Likewise, for practical purposes the values of I are in some cases shifted slightly in order that (see Figs. 3 through 11) the ideal extraction curves will intersect the ultimate wilting point at an even multiple of 6.

The discussion above describes the derivation of the adjustment table for the Waipio soil in which moisture equivalent equals 33 per cent, $P_{fwp} = 8$ per cent, and $d = 34$ inches. This table is number II in Appendix III. (Tables I, and III to IX were devised in a similar manner for the other eight soil types, but are not presented in this paper. They are available, if desired, upon request from the Agricultural department of the Experiment Station.)

Operation of Day-Degree Irrigation Interval With Assistance of Interval Adjustment Tables

The Interval Adjustment Table appearing in Appendix III is preceded by some pertinent "Explanations," "Rules for Obtaining Correction Values from Rain Tables," "Rules for Operation of Interval," and several illustrative sample field records. Some elaboration of these is necessary for a complete understanding of the tables, and the method of manipulating an interval when rainfall interferes. This elaboration is developed herewith, following the method of interval operation employed at Waipio, and using Table II for Waipio soil conditions. The examples which are provided give cases of adjustments made by each of the rules. The explanations accompanying the examples describe merely the manipulations of each adjustment.

As a start it is presumed that no rainfall will interfere with the interval. The management schedules an irrigation interval in day-degrees which is symbolized: C. In setting a value for C, the management recognizes that C is divided into two periods. The first period, A, is the portion of the interval from the date of irrigation to the date on which soil moisture is depleted to the ultimate wilting percentage. At Waipio, $A = 222$ day-degrees, as has been demonstrated in the discussion above.

The second period, B, is the portion of the interval between the date on which soil moisture reaches the ultimate wilting percentage and the date on which the next irrigation is to be applied. The value of B in day-degrees is selected by the management on a basis of experimental indications of that value of B which will produce an equal or greater yield of sugar with the least amount of total water for the crop. The value of B may also be selected on a basis of the age or variety of cane, or a number of other factors.

Experiments are under way at Waipio which should provide indications of relation of these factors to the desirable amount of B-period to be selected. Heretofore the selected B-period has been uniformly long, medium, or short throughout

the crop length. Variety differences have not as yet been considered in selecting the B-period.

Experiments 102-I and 104-I at Waipio have given satisfactory indications that the appropriate length of the B-period for H 109 cane at Waipio is approximately 150 day-degrees, after the third or fourth month of age. Treatments in Experiment 104-I, for example, in which each interval, C, included 156 day-degrees of B-period, produced an equal amount of sugar with fewer irrigations than did treatments in which the B-period was 0 day-degrees. Cane tonnage was greater in the latter case.

It is not within the sphere of this paper to discuss the physiological processes or internal water economy of the cane plant which produced the results obtained in Experiment 104-I. Plant physiologists indicate: (*a*) if the plant processes are producing cellulose (growth) at a rate approaching the maximum possible, the simultaneous production of carbohydrates (sugars) will proceed at a relatively slow rate; (*b*) if some condition is imposed upon the plant which reduces the rate of cellulose production, the rate of carbohydrate accumulation will become relatively more rapid. Whether or not the physiological processes of the H 109 cane were thus affected by the irrigation treatments of Experiment 104-I is a problem for a plant physiologist to investigate, and we propose to leave it to him. Our concern is that by certain irrigation intervals several corresponding cycles of soil-moisture conditions produced the final effects on the yields. The methods we are describing should reproduce similar conditions and results whenever they are applied.

Due to immaturity of the cane and the shallow root development up to about three months of age, a B-period of 0 to 30 day-degrees, only, is selected by the management for starting Waipio fields. The reader is cautioned to note that the day-degrees selected for the B-period at Waipio are intended for use solely at Waipio with H 109 cane, and may not be applicable elsewhere or with other cane varieties. Furthermore, it should be stated here that there has never been any intent on our part to recommend that the 350 day-degrees optimum value for the irrigation interval (C), as indicated by the first crop of Experiment 104-I, can be used universally in the irrigation of sugar cane (6).

When a field has been scheduled for an interval of C day-degrees with the expectation of receiving no rainfall, and if a rain does occur, the interval is adjusted so as to take advantage of the resulting increase in soil moisture. In this adjustment, (1) the A-period of the interval may be prolonged; (2) the desired B-period of the interval may be interrupted and a certain amount of undesired A-period be introduced into C; or (3) if there is a series of rains, both situations may develop. In any case the adjustment is made in a manner which, as nearly as possible, maintains a balance between A and B that will be proportional to the original ratio of B to A.

The existence of the wilting range is also considered in making the adjustment of the interval for the rainfall received. The wilting range, of course, occurs on the day-degree scale just prior to completion of the A part of the interval. At Waipio the wilting range appears to occur between 178 and 222 day-degrees after an irrigation. For practical purposes 180 and 220 day-degrees are used, where necessary, in adjusting for rainfall.

The use of the interval adjustment table for controlling irrigations at Waipio has demonstrated that it is impossible to utilize merely a single record of elapsing day-degrees netted for any rainfall. This would be the ideal, but since the irrigation interval *C* is composed of two parts to be balanced one against the other, and since a record of net day-degrees after the last irrigation is actually a direct function of the condition of soil moisture, an auxiliary record must be employed under certain situations as seen in the examples provided.

The form used for irrigation control may record the net day-degrees either in a vertical column or in a horizontal row. At Waipio both have been tried, but for Waipio controls, the horizontal row with dates in columns has been found more suitable. This is the form in which the examples are set up (see insert, Appendix III). The row *N* is the net day-degree interval. Row *S* could be omitted, but to avoid any possibility of accidental carelessness it is used to record the tabular setback of the *N* record due to any effective rain. Row *X* is the auxiliary record mentioned above. Its specific use is described in the "Rules for Operation of Interval," and further explanation will be offered in due course.

In the "Rules for Obtaining Correction Values from Rain Tables," Rules 1, 2 and 3 are self-evident. Rule 4 is included because any rain occurring within 24 hours of an irrigation is essentially a part of the irrigation. Rule 5 is included for the sake of conservatism. Although as little as 0.1 inch of rain, falling on cane over 12 months of age, has been observed to increase the average soil moisture, still small rains penetrate the soil to only a shallow depth.

The "Rules for Operation of Interval" cover a number of possible situations which may exist at the time a rain occurs and a number of results of the rain dependent on its amount. These rules are devised so as to treat the possible situations with a mixture of plain common sense and theory, with emphasis on common sense and a factor of safety. The rules are intended for guidance, and there is no thought that in controlling an interval the adjustment for rainfall shall be made by strict adherence to rule of thumb, with no application of the operator's sense of good judgment in evaluating observations of field conditions.

A rain may occur during an interval under two major circumstances. The first is while the interval is still within the *A*-period, *i.e.*, the *N* record is less than 222 day-degrees, at which time soil moisture would be extracted to the ultimate wilting percentage. This case is adjusted according to Rule I. The adjustment is simply a setback of the *N* record. No attempt is ever made under this case to balance the value of the remaining *B*-period against the resulting increased gross value of the *A*-period, since a series of rains can prolong to as much as three months the time before the ultimate wilting percentage is obtained, *i.e.*, until the *N* record finally reaches 222. In such a case the *B*-period, if balanced against the total gross *A*-period, would be disastrously long. Actually under Rule I the irrigation is applied when the *N* record reaches 222 plus the selected number of day-degrees for period *B*, *i.e.*, when record *N* reaches the scheduled value of *C*.

The second major circumstance, in which rain may occur, is that of a rain falling in the *B*-period of an interval *i.e.*, when record *N* is greater than 222 day-degrees. This means that there is no longer any readily available moisture in the soil of the root zone. In this case a given rain will always set the *N* record back to the same

point, regardless of how far beyond 222 the N record may be on the date the rain starts. For example: 0.70 inch of rain, occurring when $N = 230$, sets N back to 180. If the 0.70 inch of rain occurs when $N = 300$, N will be set back to 180.

In the case of a rain or series of rains occurring during the B-period, five effects of the rain may result, depending on its magnitude. These effects are accounted for under Rule II by the five sub-rules (a) to (e). The adjustment by Rules II (a), II (c), and II (e) are made in the manner described because a rain small enough to set the N record back only within the wilting range between 178 to 222 day-degrees saturates the soil to only a few inches in depth. Although the average soil-moisture content rises above the ultimate wilting percentage, the bulk of the root zone is not benefited. The use of the X record thus serves as a factor of safety in insuring that these setbacks of the N record, representing small receipts of available soil moisture, will not result in an excessive interval elapsing before the lower horizons of the root zone are refilled with moisture by irrigation. A further consideration is that the amount of A-period introduced by the rain is so small that the proportional B-period to be allowed before irrigation would be negligible, hence it is better to proceed as per these three rules.

Rules II (b) and II (d) are the means by which a new proportional balance is obtained between the B- and A-periods when a rain or series of rains set the N record back of the wilting range, *i.e.,* the adjustment from the Rain Table sets record N back to less than 178. The attitude in correcting for this rain is that it is a fractional irrigation, and as such essentially stops the interval that was in progress at the time. A new interval of fractional magnitude, which must be calculated, is thus commenced. In this case the rain has saturated the root zone to a sufficient depth that the resulting fractional A-period is large enough to be balanced by a proportionally fractional B-period. The simple equation given calculates this fractional B-period and simultaneously adds it to the end of the A-period to give a revised interval, C', at which point on N record the next irrigation would be applied.

Notice that if a series of rains occurs under Rules II (b) or II (d), the setback of *least* value is used to calculate the revised interval, C'. The reason for this is that such a value for calculating C' provides a factor of safety in preventing the fractional B-period from being too large, as might be possible when a series of rains maintained soil moisture above the ultimate wilting percentage for a considerable length of time. That is, the setbacks due to this series of rains would hold the N record for some time at values less than 222, and it would be dangerous to calculate C' using for S the total day-degrees from the first rain which set N back of 178, to the date on which N reached 222 day-degrees.

Soil Types Differing From Waipio Conditions

The rules upon which comments were offered just above are general in nature and are applicable to other soil types and conditions than are found at Waipio, *providing* that corrections for rainfall are obtained from the *proper* adjustment table. Table II which has been described at length in this paper was designed specifically for Waipio soil. It is believed that this table may be used for other localities where the moisture capacity of the soil and depth of root zone are equivalent to those at Waipio. The other eight tables are intended for use on other soil

types, as indicated on the face of each table. The moisture equivalent is used as one index for classifying moisture-holding capacity of a soil, and the depth of root zone is given in inches for the other index of soil type. Since moisture equivalent varies considerably in value, the three classifications of this index appearing on the tables are given as a range of moisture equivalent in each case.

In selecting the proper adjustment table for a given field or fields, a knowledge of the moisture capacity, which can be indicated by moisture equivalent, and of the depth of root zone, which can be more or less readily determined, is necessary. Consultation with Experiment Station representatives should also assist in selection of the proper table and its use in controlling irrigation intervals. By no means should the adjustment table be selected hastily without a preliminary study of soil conditions. Some experimentation should be included for the purpose of determining for specific localities and conditions the proper length of the *B*-period to be included in scheduled intervals.

Again it is to be emphasized that, while day-degree controlled intervals are under operation with the aid of the adjustment table, personal surveillance of field conditions and general appearance of the cane should be employed in tempering the adjustment rules with plain common sense, and a small degree of conservatism.

As typical of the suggested conservatism, we would refer the reader to our Table IX which was constructed from Fig. 11. A sandy soil of shallow depth, say not over 17 inches, would require the use of this table in adjusting for rainfall. Fig. 11 indicates that the soil moisture will be extracted from this soil to the ultimate wilting point in about 50 day-degrees. The conservative attitude toward the operating of intervals and the adjusting for rainfall on this soil would be to use only Rule I, Rule II (*a*), and Rule II (*c*). No consideration should be given to possibilities of using Rules II (*b*), II (*d*), or II (*e*), thus avoiding any chance of damage to the cane. Furthermore, in this case time is so short except in winter, that any attempt to balance the *B*-period against any unexpected fractional *A*-period would result in a revised interval, *C′*, differing from the original scheduled interval, *C*, by only a few day-degrees. This would be equivalent to a fractional day or two at most. Such an attempted revision of *C* would be a waste of effort as the irrigation would probably be applied on the same date as under the original *C*.

Conclusion

This paper has described how the problem of rainfall evaluation has been dealt with at the Waipio Substation of the Experiment Station, H. S. P. A. A workable, practical method of rain evaluation has been offered which combines scientific theory, recognition of the character and influence of conditions observed in the field, and a reasonable degree of conservatism.

In presenting the table of adjustments for rainfall for use at Waipio, the derivation of the adjustments has been described in detail. Rules have been presented for operating a day-degree-measured irrigation interval with the aid of the adjustment table. Reasons for the nature of these rules have been explained.

In the course of deriving the adjustments, a revised concept of the term "permanent wilting percentage" is discussed. Attention is invited to the "wilting range"

and later its significance in affecting the method of applying the interval adjustments is explained.

It is mentioned that eight other adjustment tables have been similarly devised and are available upon request. It is believed that these tables should provide for evaluating rainfall on soil types differing from that of Waipio.

The reader is cautioned against using universally the Waipio adjustment table and the intervals scheduled at Waipio. Individuals are urged to study their own specific soil types with the assistance of the Experiment Station, and thus select the most appropriate table for their conditions. Experimentation to determine the local optimum interval is suggested as an adjunct to successful use of that table suitable for a given soil type.

Appendix I

Soil Moisture—Rainfall—Interval Computations

A—Explanation of Symbols Used in Equations:

MFC = Maximum field capacity of the soil (% on dry basis).
FWP = First permanent wilting percentage of the soil (on dry basis).
UWP = Ultimate permanent wilting percentage of the soil (on dry basis).
V = Volume weight of the soil. (1.1 is used in the equations below, as it is a reasonable average of the volume weight of majority of Hawaiian soils. This is a value satisfactory for general purposes as variation of volume weights lies within a small range.)
P = The range of soil moisture under consideration. (In the equations below this is expressed decimally, per equation No. 2.)
P_{fwp} = % soil moisture available to the cane plant between maximum field capacity and first permanent wilting percentage, *i.e.*, $MFC - FWP$. (This is a specific value for P.)
D = Depth of surface application of water, expressed in inches, equivalent to P.
d = Depth of soil mass involved, expressed in inches.
I = Interval in day-degrees from MFC to FWP, with no interference by rainfall.
R = Rate of soil-moisture extraction as expressed by I/D.

B—Equations Used in Soil-Moisture Computations:

No. 1 $D = P \times V \times d$ (This is the general equation expressing the manner in which the soil becomes saturated by a surface application of water.)

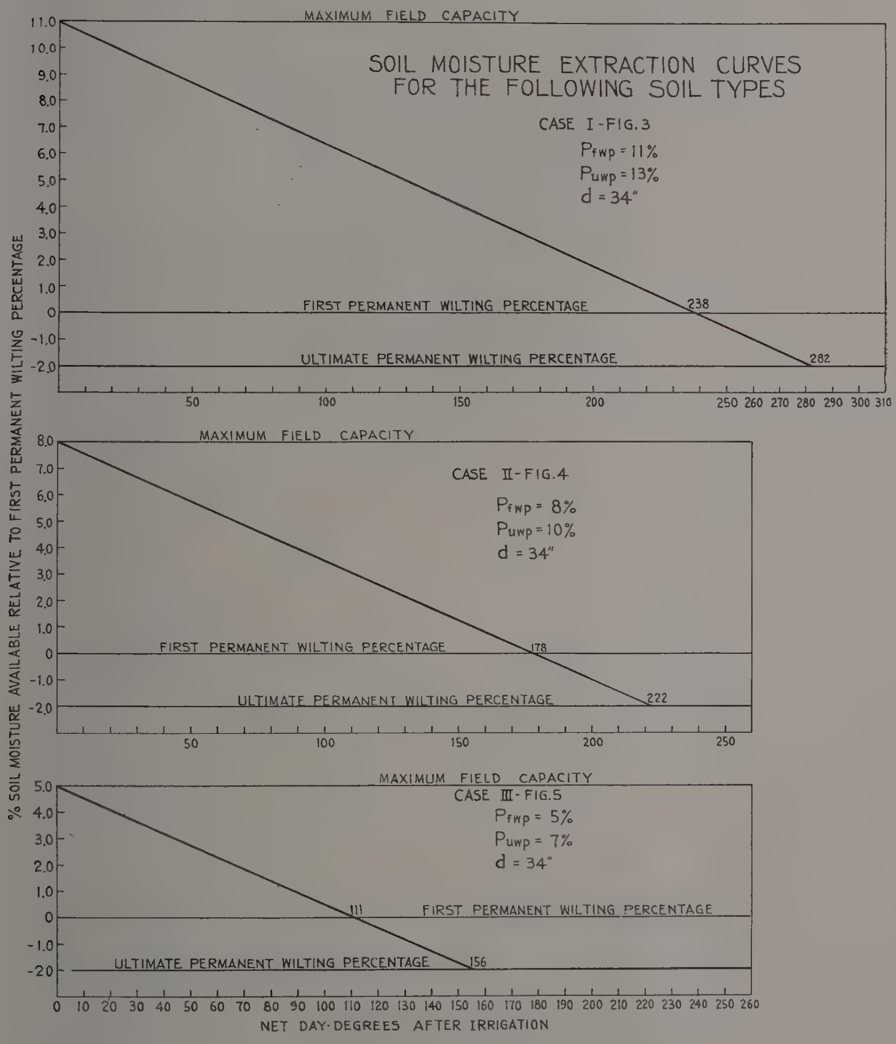
No. 2 $P_{fwp} = \frac{(MFC - FWP)}{100}$ (This equation merely converts P_{fwp} from % to a decimal value for use where P_{fwp} appears in the equations below.)

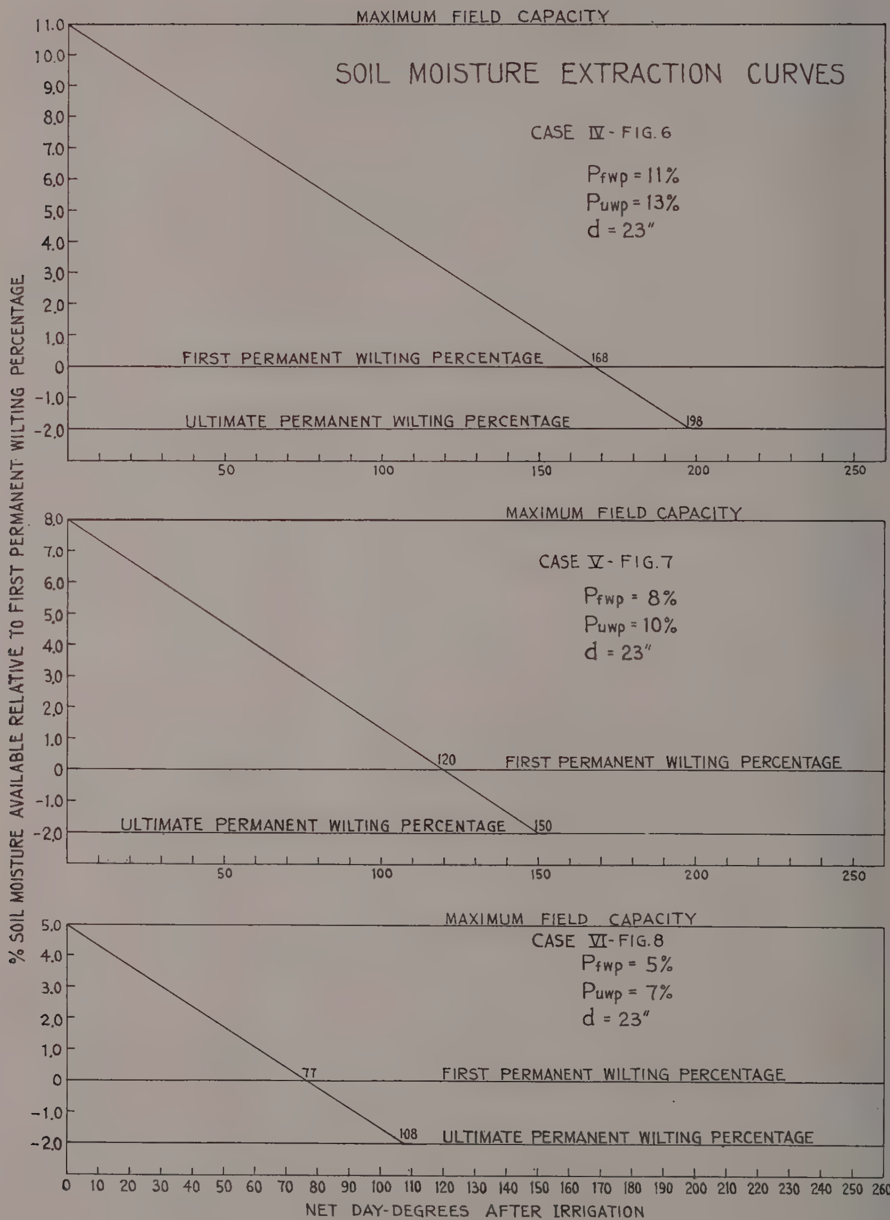
No. 3 $R = I/D = \frac{I}{P_{fwp} \times V \times D}$

No. 4 $I = R \times D = R \times P_{fwp} \times V \times d$

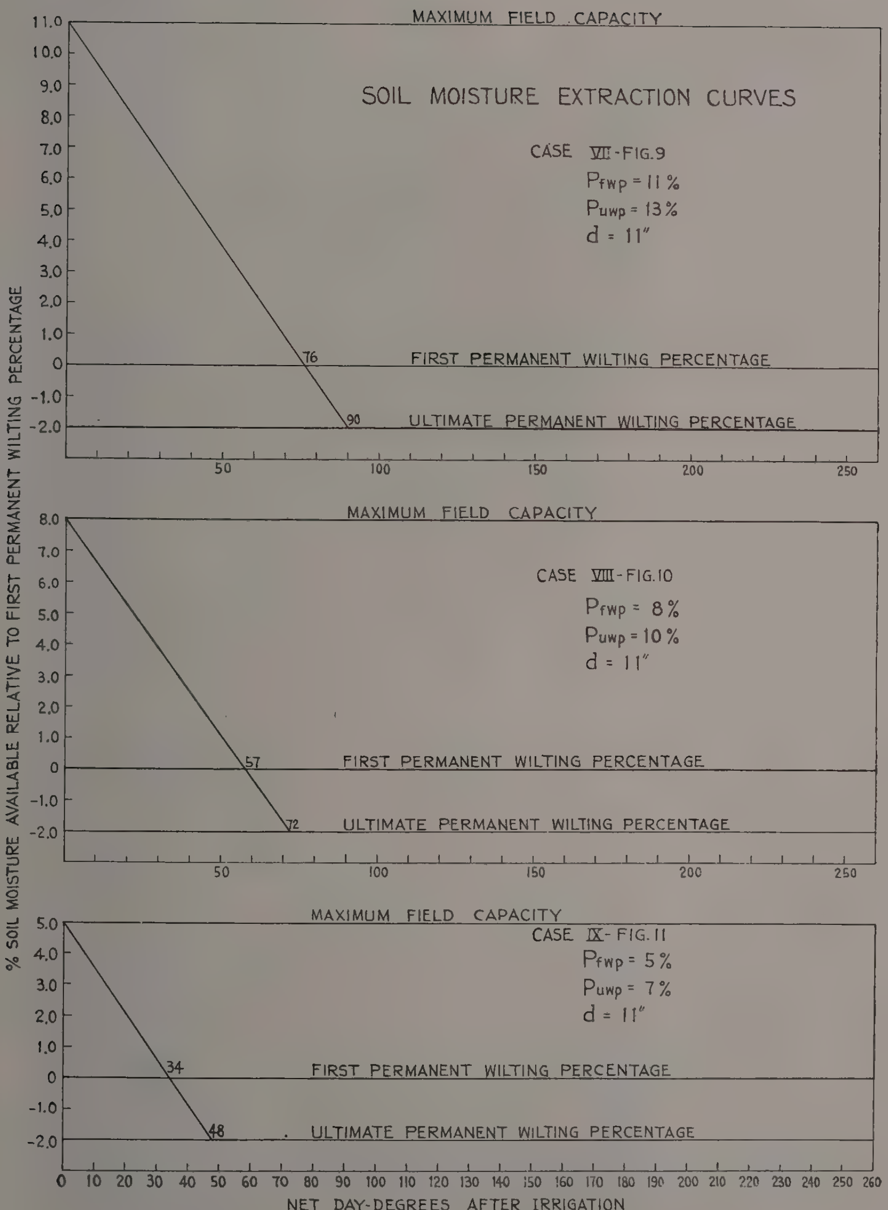
Appendix II

Figs. 3–11. These graphs indicate the different day-degree periods between irrigation and the date on which available soil moisture is completely extracted. They indicate definitely that the specified irrigation interval must be scheduled with respect to the moisture-holding capacity of the soil and the depth of the effective root mass.





SOIL MOISTURE EXTRACTION CURVES
MAXIMUM FIELD CAPACITY
CASE IV - FIG. 6
Pfwp = 11%
Puwp = 13%
d = 23"
FIRST PERMANENT WILTING PERCENTAGE
168
ULTIMATE PERMANENT WILTING PERCENTAGE
198
11.0
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0
-1.0
-2.0
50
100
150
200
250
MAXIMUM FIELD CAPACITY
CASE V - FIG. 7
Pfwp = 8%
Puwp = 10%
d = 23"
120
FIRST PERMANENT WILTING PERCENTAGE
ULTIMATE PERMANENT WILTING PERCENTAGE
150
MAXIMUM FIELD CAPACITY
CASE VI - FIG. 8
Pfwp = 5%
Puwp = 7%
d = 23"
77
FIRST PERMANENT WILTING PERCENTAGE
108
ULTIMATE PERMANENT WILTING PERCENTAGE
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200 210 220 230 240 250 260
% SOIL MOISTURE AVAILABLE RELATIVE TO FIRST PERMANENT WILTING PERCENTAGE
NET DAY-DEGREES AFTER IRRIGATION


SOIL MOISTURE EXTRACTION CURVES
MAXIMUM FIELD CAPACITY
CASE VII - FIG. 9
Pfwp = 11 %
Puwp = 13 %
d = 11"
76
FIRST PERMANENT WILTING PERCENTAGE
90
ULTIMATE PERMANENT WILTING PERCENTAGE
MAXIMUM FIELD CAPACITY
CASE VIII - FIG. 10
Pfwp = 8 %
Puwp = 10 %
d = 11"
57
FIRST PERMANENT WILTING PERCENTAGE
72
ULTIMATE PERMANENT WILTING PERCENTAGE
MAXIMUM FIELD CAPACITY
CASE IX - FIG. 11
Pfwp = 5 %
Puwp = 7 %
d = 11"
34
FIRST PERMANENT WILTING PERCENTAGE
48
ULTIMATE PERMANENT WILTING PERCENTAGE
% SOIL MOISTURE AVAILABLE RELATIVE TO FIRST PERMANENT WILTING PERCENTAGE
NET DAY-DEGREES AFTER IRRIGATION

Appendix III

Explanations

C: The interval for irrigation, scheduled by management. This is divided into two periods: *A* and *B*, of which—

A: Is the portion of the interval before the ultimate wilting percentage, which is determined by moisture equivalent and depth of soil; and—

B: Is the portion of the interval that is below ultimate wilting percentage; the length of this period is selected by the management.

Wilting Range: The difference in soil moisture from the first wilting percentage to the ultimate wilting percentage.

First Wilting Percentage (*FWP*): The amount of moisture in the soil when the cane growth rate shows first retardation.

Ultimate Wilting Percentage (*UWP*): The amount of moisture remaining in the soil which the plant cannot extract.

The first and ultimate wilting percentages appear on the Interval Adjustment Tables in terms of day-degrees.

In the explanations following the examples it is presumed that no rain will interfere with *C*. In case rain interferes, the rules below provide the means for making the proper adjustments.

In the record of the progressing interval:

Row or column *N:* The net day-degree interval, as adjusted for any rainfall which occurs.

Row or column *S:* The setback adjustment at the time of rain, as obtained from the adjustment tables.

Row or column *X:* An auxiliary record to be used as described in the rules which follow:

Operation of Day-Degree Irrigation Interval With the Aid of Interval Adjustment Tables

See examples which follow:

Rules for Obtaining Correction Values From Rain Tables.

(1) Enter the table with the rainfall taken to the nearest 0.1 inch.

(2) Interpolation can be made vertically and horizontally between tabular values.

(3) Adjust for each day's rainfall.

(4) Ignore any rain falling within 24 hours after irrigation or after net interval = 0.

(5) In cane over 12 months of age, ignore as ineffective any rain less than 0.25 inch.

Rules for Operation of Interval

I *Rain occurring during period A.*

(1) Correct record *N* for rain, according to adjustment table.

(2) Irrigate when *N* reaches selected interval.

II *Rain occurring during period B.*

(*a*) If the rain is of such proportion that the rain correction from the table causes a setback of the interval within the wilting range only—

(1) Correct record N and continue record.

(2) In record X, continue, without correction, the record in N.

(3) Irrigate when record X reaches scheduled interval.

(*b*) If rain is of such proportion that the rain correction from the table sets the record N back of the wilting range into period A.

(1) Correct record N and continue record until end of period A.

(2) When record N next reaches period B, calculate a revised value for C (C' in the equation below):

$$C' = A + \frac{B \times (A - S)}{A}$$

In which S = the correction having the smallest value while record N was in the period A.

(3) Irrigate when record N reaches C'.

(*c*) If additional rains occur after correction II (*a*), and are of such proportion that the record N remains in the wilting range—

(1) Correct record N.

(2) Continue record X.

(3) Irrigate when record X reaches schedule.

(*d*) If additional rains occur after above correction II (*a*), and are of such proportion that record N is setback of the wilting range—

(1) Apply rule II (*b*).

(2) Discontinue record X.

(*e*) If additional rains occur after above correction II (*b*), and are of such proportion that record N is setback into the wilting range—

(1) Apply rule II (*a*).

(2) Irrigate when record X reaches C'.

Description of Operation of Intervals in Examples Given

Four examples of field records will be described to illustrate the "Rules for Operation of Day-Degree Interval with the Aid of Interval Adjustment Tables."

The fields used are presumed to be located at Waipio Substation, and to be less than 12 months of age. The depth and characteristics of Waipio soil require the use of Adjustment Table II in correcting for rainfall. In the examples all rainfall corrections appearing in Row S were obtained from Table II.

On the form for the field record, the second column is headed "C Interval." In this column the scheduled day-degree interval for each field has been noted.

The third column is headed "A- and B-Periods." In this column the upper figure noted (220) is the A-period, the number of day-degrees which the moisture equivalent of Waipio soils indicates will be accumulated from the date of irrigation to the date on which soil moisture reaches the Ultimate Wilting Percentage. The lower figure is the B-period, the number of day-degrees which the management wishes to have accumulate after the soil moisture reaches the Ultimate Wilting Percentage before applying the next irrigation.

EXAMPLES OF INTERVAL ADJUSTMENTS FOR RAINFALL

Using Table II

I = Irrigation applied

OCTOBER 1941

Field no.	C interval	A-&B-per.	Date	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
			Day °	16	19	18	19	17	20	20	12	11	17	18	16	16	15	14	15	16	15	17	17	15	17	13	7	9	13	19	21	17	16	21
			Rain							.28	.17	.07					.06	.02			.04					1.26	.45				.08	.07		
		220	S						91	99	105					177								I	0	0				42	57			
A	300	80	N	16	35	53	72	89	109	111	111	116	133	151	167	183	192	206	221	237	252	269	286	301	17	13	7	16	29	48	63	74	90	111
			X																															
		220	S						204	210	216					216				I					3	0				42	57			
B	400	180	N	148	167	185	204	221	241	224	222	227	244	262	278	294	231	245	260	276	15	32	49	64	81	16	7	16	29	48	63	74	90	111
			X						241	261	273	284	301	319	335	351	366	380	395	411														
		220	S		I				56	64	70					142									144	127				169	184		C′ =	254
C	300	80	N	314	333	18	37	54	74	76	76	81	98	115	132	148	157	171	186	202	217	234	251	266	283	157	134	143	156	175	190	201	217	238
			X																															
		220	S						138	146	152					216									144	127				169	184		C′ =	286
D	375	155	N	63	82	100	119	136	156	158	158	163	180	198	214	230	231	245	260	276	291	308	325	340	357	157	134	143	156	175	190	201	217	238
			X													230	245	259	274	290	305	322	339	354	371									

NOVEMBER 1941

Field no.	C interval	A-&B-per.	Date	1	2	3	4	5	6	7	8	9	10
			Day °	22	18	17	18	18	18	17	15	16	
			Rain		.27	.31							
		220	S	204	204	I							
D	375	155	N	260	222	221	18	36					
			X	260	278	295							
		220	S	I									
C	300	80	N	260									
			X										

The sum of A and B gives the value for C, and if no rain interferes during either period A or B, then irrigations would be applied whenever the day-degrees have accumulated to the value in Column C. The rules illustrated, herewith, provide for maintaining a balance, in spite of rain, between A and B proportional to the values appearing in the column headed "A- and B-Periods."

Field A:

This field had a scheduled interval of $C = 300$ Net Day-Degrees. The A-period was, of course, 220 day-degrees, and the management desired to have 80 day-degrees for the B-period of the interval.

This field was irrigated (irrigation was started at the control point in the field) on September 30. Day-degrees were accumulated in the record (or row) N until October 6 when $N = 109$. Rain of 0.28 inch fell on October 6-7. Table II shows that 0.28 inch of rain coming at 109 day-degrees sets the N record back to 91, this amount being recorded in row S on October 6. From October 6-7, 20 day-degrees were received (noted on October 7). This added to 91 gives 111 which is recorded in row N on October 7.

On October 8 the N record was set back from 111 to 99 in row S by the 0.17 inch of rain falling on October 7-8. Simultaneously, 12 day-degrees were received, so the N record reads 111 ($99 + 12 = 111$) on October 8.

On October 8-9, 0.07 inch of rain set the N record of 111 on October 8 back to 105 in the S record—$105 + 11 = 116$, as appears in the N record on October 9.

A rainfall of 0.06 inch on October 13-14 set the N record of 183 on October 13 back to 177 in row S.

Since the four rains noted above each came when the N record was less than 220, the interval was in the period A and Rule I was applied, the next irrigation being started on October 21 when the N record reached 301 in accordance with the scheduled interval, C.

Notice that, according to Rule (1) of the "General Rules for Obtaining Correction Values from Rain Tables," the rains of October 14-15, and October 17-18 were ignored, being too small to consider as 0.10 inch for tabular correction.

From the irrigation on October 21 to the end of October, Rule I was again used four times, when rains were received while the interval was in period A.

Field B:

This field had a scheduled interval of $C = 400$ Net Day-Degrees, with the A-period being 220 day-degrees. The management desired to have 180 day-degrees for the B-period of the interval.

The field was irrigated in September, the interval reaching 241 net day-degrees on October 6, as noted in the N row. The 0.28 inch of rain on October 6-7 set the interval back from 241 to 204 in row S on October 6. The interval was in period B on October 6, and the rain set it back into the wilting range (204 being between 180 and 220). Therefore Rule II (a) was applicable, and the value of N on October 6 was repeated in row X and day-degrees were accumulated in this row without correction.

The 0.17-, 0.07-, and 0.06-inch rains of October 7-8, 8-9, and 13-14, respectively, each set the interval back within the wilting range. In these cases Rule II (c) was

applicable. Row N was corrected each time to the value in row S, but row X was continued without correction. When row X reached 411 on October 17, a new irrigation was started. It was considered advisable to irrigate on October 17, after the X record had passed 400, rather than on October 16, before X reached 400.

From the irrigation on October 17 to the end of the month four rains occurred, each time with the interval in period A, and Rule I was applied.

Field C:

This field had a scheduled interval of $C = 300$ Net Day-Degrees, with period $A = 220$ Day-Degrees, and period-B selected by management to be 80 day-degrees.

This field received an irrigation on October 2. The rains of October 6-7, 7-8, 8-9, and 13-14, each occurred when the interval was in period A, and consequently Rule I was applied.

The 1.26-inch rain on October 22-23 set the interval back from 283 in row N to 144 in row S on October 22. The interval was in period B and was setback of the wilting range into period A, the value of S, 144, being less than both 180 and 220. Therefore, Rule II (b) was applied. Row N was corrected, as stated, on the 22nd and also on October 23, 27, and 28 for other rains. Each of these setbacks was within the period A but record N passed from period-A to period-B on October 30. Having gone through a fractional portion of an A-period, it was necessary to revise the value of the interval, C, so that the B-period would be proportionally smaller. This was done on October 30 as described in Rule II (b), a revised value for interval C being calculated as follows:

For S in the equation of Rule II (b), it was found that between October 22 and 30, the smallest setback value in row S was 127 on October 23. The revising equation thus read:

$$C' = 220 + \frac{80 \times (220 - 127)}{220} = 220 + \frac{80 \times 93}{220} = 220 + 34 = 254$$

This value for C' is noted in the field record for reference as to when the next irrigation should start. (See row S, on October 30. It could be noted anywhere else that might be convenient. At Waipio it is noted with red pencil in same location as this example.) When the record N reached 260 on November 1, the next irrigation was started.

Field D:

This field had a scheduled interval of $C = 375$ Net Day-Degrees with 220 for the period A, and 155 selected by the management for period B.

This field was irrigated the latter part of September, and the N record reached 156 on October 6, on which date it was setback to 138 in row S by the 0.28-inch rain of October 6-7. This was a case for Rule I, as were also the effects of the rains on October 7-8 and 8-9.

The interval continued and passed into period B. Then on October 13 with N at 230, the rain of October 13-14 set the interval back to 216 which was within the wilting range. Rule II (a) was applicable in this case. The correction to N was made, as seen in row S, and the N record was continued in row X without correction. The N and X records were continued, reaching 357 and 371, respectively, on October 22. The next irrigation would have been applied as soon as possible

after this date, the X record having reached approximately the scheduled interval (C). However, a heavy rain commenced on the morning of the 22nd which was sufficient to cause a setback of the N record to 144, or into period A back of the wilting range. Rule II (d) was applicable, and consequently, the N record was corrected, as seen, while the X record was discontinued. Several other rains occurred, each setting the interval back into the A-period. When the N record passed into the B-period on October 30, a revised value for C was calculated, using 127 for the value of S in the equation:

$$C' = 220 + \frac{155 \times (220 - 127)}{220} = 220 + \frac{155 \times 93}{220} = 220 + 66 = 286$$

This value was noted on the field record, for reference as to when next to irrigate. Another rain on November 1-2 interfered by setting the N record back to 204 in row S on November 1. This setback put the interval into the wilting range, hence Rule II (e) was applicable. The N record was corrected, as stated, and a new X record was started. The field was irrigated when the X record reached 295 on November 3.

INTERVAL ADJUSTMENT TABLE II

FOR SOILS WITH FOLLOWING CHARACTERISTICS:

Depth of Effective Root Zone—34 inches
Moisture Equivalent of Soil—25–36%
Wilting Range—
FWP occurs at 178 day-degrees
UWP occurs at 222 day-degrees

Position of interval in day-degrees at start of rainfall	Inches of rainfall													
	0.1	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0	2.2	2.4	2.5
6	0													
12	6	0												
18	12	6												
24	18	12	0											
30	24	18	6											
36	30	24	12	0										
42	36	30	18	6										
48	42	36	24	12	0									
54	48	42	30	18	6									
60	54	48	36	24	12	0								
66	60	54	42	30	18	6								
72	66	60	48	36	24	12	0							
78	72	66	54	42	30	18	6							
84	78	72	60	48	36	24	12	0						
90	84	78	66	54	42	30	18	6						
96	90	84	72	60	48	36	24	12	0					
102	96	90	78	66	54	42	30	18	6					
108	102	96	84	72	60	48	36	24	12	0				
114	108	102	90	78	66	54	42	30	18	6				
120	114	108	96	84	72	60	48	36	24	12	0			
126	120	114	102	90	78	66	54	42	30	18	6			
132	126	120	108	96	84	72	60	48	36	24	12	0		
138	132	126	114	102	90	78	66	54	42	30	18	6		
144	138	132	120	108	96	84	72	60	48	36	24	12	0	
150	144	138	126	114	102	90	78	66	54	42	30	18	6	0

Note: Data in body of this table represent position of irrigation interval as changed by rainfall. (J.A.S. 9/9/41.)

Position of interval in day-degrees at start of rainfall	Inches of rainfall: 0.1	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0	2.2	2.4	2.5
156	150	144	132	120	108	96	84	72	60	48	36	24	12	6
162	156	150	138	126	114	102	90	78	66	54	42	30	18	12
168	162	156	144	132	120	108	96	84	72	60	48	36	24	18
174	168	162	150	138	126	114	102	90	78	66	54	42	30	24
180	174	168	156	144	132	120	108	96	84	72	60	48	36	30
186	180	174	162	150	138	126	114	102	90	78	66	54	42	36
192	186	180	168	156	144	132	120	108	96	84	72	60	48	42
198	192	186	174	162	150	138	126	114	102	90	78	66	54	48
204	198	192	180	168	156	144	132	120	108	96	84	72	60	54
210	204	198	186	174	162	150	138	126	114	102	90	78	66	60
216	210	204	192	180	168	156	144	132	120	108	96	84	72	66
222+	216	210	198	186	174	162	150	138	126	114	102	90	78	72

Position of interval in day-degrees at start of rainfall	Inches of rainfall: 2.6	2.7	2.8	2.9	3.0	3.1	3.2	3.3	3.4	3.5	3.6	3.7+
156	0											
162	6	0										
168	12	6	0									
174	18	12	6	0								
180	24	18	12	6	0							
186	30	24	18	12	6	0						
192	36	30	24	18	12	6	0					
198	42	36	30	24	18	12	6	0				
204	48	42	36	30	24	18	12	6	0			
210	54	48	42	36	30	24	18	12	6	0		
216	60	54	48	42	36	30	24	18	12	6	0	
222+	66	60	54	48	42	36	30	24	18	12	6	0

Appendix IV

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Sugar Prices

96° CENTRIFUGALS FOR THE PERIOD DECEMBER 1, 1941 TO MARCH 15, 1942

Date	Per pound	Per ton	Remarks
Jan. 5, 1942.............	3.74¢	$74.80	Philippines.

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